

**THERMALLY ASSISTED FRACTURING OF ANCIENT ROCK SURFACES DUE TO
ENVIRONMENTAL EFFECTS:
THE CASES OF THE VALLEY OF THE KINGS (EGYPT) AND LÅNGÖREN ISLAND
(FINLAND)**

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To my angels,

Mami Nora & Andrea

(2022)

ABSTRACT

Temperature fluctuations from climatic cycles can induce thermo-mechanical fatigue, impacting the stability of rock masses, specially in shallow bedrocks and slopes. This research investigates the mechanism driving fatigue at two distinct environments: Långören Island in Finland and the Valley of the Kings in Egypt.

Installed monitoring systems at these locations continuously track rock slabs subjected to temperature cycles. The sensors recorded annual deformation ratios of 0.04 mm/°C for Finland and 0.05 mm/°C for Egypt, indicating cumulative fatigue effects over time. Limited literature on deformation ratios complicates comprehensive comparisons. Mechanical and thermal conditions were documented through geological mapping and laboratory tests, while 2D finite-difference numerical models were developed using FLAC®. For Långören Island, a linear correlation between measured and simulated data yielded an R^2 of 0.85, with a slope of 0.5 and an intercept of 0.45 mm, indicating the need for further calibration. In contrast, the Valley of the Kings model achieved a slope of 0.85 and a lower intercept of 0.001 mm, with a similar correlation ($R^2 = 0.80$), suggesting a better match between measured and simulated data. Despite the similar R^2 values, the shorter study period at Långören Island likely led to greater data scatter, affecting the overall fit, whereas the longer-term monitoring at the Valley of the Kings allowed for refined modeling of site-specific factors.

In the Valley of the Kings, observed conditions and the site's complex geometry prompted the development of a thermo-mechanical model in FLAC3D®. A calibrated 3D model was used to explore transient conditions from April 2018 to March 2019, with a 156 different variations used including localized plasticity to account for inelastic displacements recorded through July 2023. The simulations correlated with measurements, yielding an R^2 of 0.90, a slope of 0.65, and intersection of 0.3 mm for the first 12 months from April 218 to March 2019.

A conceptual approach using Goodman's diagram, related mean and alternating deviatoric stresses to assess fatigue failure. A novel thermo-mechanical fatigue criterion based on crack initiation stress thresholds of 11.4 MPa for the Valley of the Kings predicts further crack growth due to thermal fluctuations. This framework can be applied to various scenarios involving natural rocks and concrete structures subjected to environmental temperature changes, linking material properties to fatigue failure mechanisms. Understanding thermal fatigue is crucial to preserving natural cliffs and rock built infrastructure of cultural significance, ultimately improving rock engineering design resilience to safeguard for the future.

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CHAPTER 1 INTRODUCTION

1.1 Research Motivation

Stability evaluation of engineering structures situated upon or within rock masses typically entails the delineation of structural zones, distribution of stress, material strength and resilience, and rock support needed or existing to support the rock mass. When incorporating these inputs into mechanical static models, sometimes the outcomes are not sufficient to explain the failure of structures. These models may incorporate specific inputs for seismic activity, precipitation and phreatic level variations, and freeze-thaw cycles in more sophisticated dynamic simulations. Through such scenarios, potential triggers for the stability concerns of both natural and man-made structures can be assessed. Nonetheless, this approach fails to fully elucidate the time-dependent behaviour of a rock mass over both short and long durations. This deficiency arises from the limited knowledge of dynamic inputs and their interactions, including sources of thermal energy, water flow, wind patterns and variations in air humidity and temperature; as well as a lack in observations to explain the impact on building stresses and deterioration of material properties.

Direct observations of thermal energy actively contributing to rock fracturing under outdoor conditions are very limited to studies from the early 2000's onwards, although geomorphological studies for rockslides linked to environmental conditions date back to the 30's (Merrien-Soukatchoff and Gasc-Barbier 2023). The word “contributing” is used carefully in this dissertation, since it is challenging to isolate the specific role of the temperature in outdoor scenarios amongst many other factors which include, air temperature, precipitation, solar radiation, wind speed and direction, to list some.

The notable fracturing at Twain Harte dam (California, USA) during exceptionally hot days in July 2014 (peak temperatures ranging between 30°C and 40°C) showcases thermal energy driving spontaneous rock fracturing (Collins et al. 2018, video at: <https://www.youtube.com/watch?v=DNdpqeJEPoY>, last accessed 01/03/2024). These events led to what Collins et al. (2018) described as “energetic (i.e., critical and explosive) fracturing”, resulting in water leakage in the dam foundation along fractures that defined exfoliated layers of 10 to 45 cm in thickness, prompting concerns of potential flooding or abutment failure of the dam. Subsequently, the geological engineering community directed its attention towards this phenomenon, conducting monitoring and studies not only on the 2014 occurrences, but through ongoing monitoring they were also able to document subsequent events in 2015 and 2016.

Similarly, during July 2014, though a long distance from California, a comparable dynamic cracking event was also documented on Långören Island in the Finish Archipelago of Finland. Throughout this period, temperatures reached 30°C, a record high for the region, resulting in the horizontal propagation of an exfoliation fracture and subsequent opening of layers within a dome-shaped rock mass. To investigate the resulting fractured area, a site exploration including geomorphological and geotechnical mapping, along with ground penetrating radar scans and a single borehole was undertaken; accompanied by the instrumentation of the site to monitor the outdoor conditions and rock mass response in the coming years. These activities were documented by Rantanen (2016), Leith et al. (2017) and Alcaïno-Olivares et al. (2018).

It is likely that thermo-mechanical (TM) fatigue processes were essential at both the Twain Harte dam and Långören Island. However, the complexity of these sites is exacerbated by other factors that could be driving crack growth such as weathering, rainfall, humidity, human activities, natural biological processes, mineral growth, and residual strain of paleotectonic origin. Hence, isolating the thermally driven mechanism under outdoor conditions will aid in discerning the circumstances and ramifications of rock cracking under thermo-mechanical fatigue, which prompted an exploration of the following central inquiries:

1. What are the principal constituents of the documented site data, encompassing aspects of meteorological, geological and topographical conditions, that correspond to observations of cyclical occurrences of crack opening and closure?
2. In the near-surface bedrock environments, what are the mechanistic influences of the main triggering agents on the initiation, extension, and closure of macro-scale cracks?
3. What precisely is the role of thermally induced stress in fostering crack propagation within near-surface bedrock environments, and what specific conditions are necessary to facilitate this process of crack expansion?

In this context, the mechanisms governing subcritical crack growth leading to visible crack extension have been documented under varying conditions and rates (e.g. Bakun-Mazor et al. 2013, Vlcko et al. 2009, Marmoni et al. 2020). However, it is not consistently the case that an instantaneous and energetic response is expected to occur spontaneously and ephemeral; rather, sustained variations in stresses are integral to the fatigue process and the most common observations worldwide (Merrien-Soukatchoff and Gasc-Barbier 2023).

Another site located at the Theban Mountains (Luxor, Egypt), has been recently investigated for thermo-mechanical crack propagation (Alcaïno-Olivares et al. 2019, Alcaïno-Olivares et al. 2020).

The valley of the Kings (KV) lies on the northern side of the Theban Mountains and its famous burial sites were constructed by the ancient Egyptians around 2500 – 3000 BC (Reeves and Wilkinson, 2008). Numerous archeological teams have excavated the area to uncover underground tombs, numbered as KV##, with the most recent discovery being KV64 in 2011 (Bickel and Paulin-Grothe, 2012). The KV is exposed to high rates of solar radiations and undergo significant average daily air temperature fluctuations of 20°C between night and day.

The valley is surrounded by subvertical cliffs composed of marly and micritic limestones, which are jointed, forming overhanging blocks with sliding and toppling potential (Lukovic et al., 2021). A rock column attached to the valley's cliff, above tomb KV42, has been recognized since the 1930's as having the potential for toppling, yet did not fail to this day (Weeks and Hetherington, 2006). The column hangs at the entrance of tomb KV42 which currently is not open to tourists, and further rehabilitation works in the tomb require safe access. Our team was granted in 2018, the permission to monitor the column with an integrated system that measures displacement of the column, rock temperature, ambient conditions and rock temperature distribution within the rock mass. Monitoring data from April 2018 has revealed incremental displacement trends and irreversible, i.e. inelastic, deformations over the past six years. However, no additional cracks have been observed on the rock surface, despite the potential for thermo-mechanical fatigue. This suggests that the stability of the column may be reliant on fracture formations processes that run at a slower pace compared to those reported from Twain Harte dam and Långören Island.

These two case studies, Långören Island and the Valley of the Kings, present an opportunity to investigate thermo-mechanical cycles in rock masses across diverse climatic, geological, and topographical contexts. Consequently, distinct rock mass behaviours have been observed, and the utilization of instrumentation and data analysis has facilitated the development of a methodology to instrument and analyse this phenomenon across various environments. Although in this work, the Valley of the Kings case is subject to more extensive examination compared to that of Långören Island, the latter served as the starting point for validating concepts related to thermo-mechanical fatigue. It is paramount to emphasize that comprehending the long-term impacts of rock mass exposure and its response holds critical significance for engineering practice. As climate change intensifies and pressure mounts to prolong the lifespan of existing infrastructure whilst encountering new design challenges, such understanding becomes increasingly indispensable. Moreover, the insights gained from this study can positively impact the approaches taken to maintain and enhance the durability of contemporary structures.

1.2 General Background

This research centers on exploring the impact of thermally assisted deformations on fracture development resulting from thermo-mechanical fatigue processes. Consequently, it extensively delves into concepts such as thermal stresses and strains, variations in rock surface temperature related to environmental parameters, and thermo-mechanical fatigue. Hence, it is imperative to provide a brief introduction to these concepts before delving into an extensive literature review of the current state-of-the-art, thereby aiding the reader in grasping the fundamentals of this dissertation.

1.2.1 Thermal stress and strain

Understanding thermal stress and strain concepts is imperative in the context of thermo-mechanical fatigue. Primarily, due to disparities between the notions of strength and thermal stress resistance in brittle materials. For instance, the propagation of microscopic cracks within a thermally loaded body is consistently observed within stress fields characterized by inhomogeneity, which include regions of both tensile and compressive stresses. Additionally, thermal stresses caused by thermal deformation tend to dissipate quickly due to temperature fluctuations, unlike the slow relaxation of externally applied mechanical loads, which are more stable. Particularly, for thermo-mechanical cycling scenarios, local stresses emerge within structurally heterogeneous bodies, not solely due to elastic anisotropy but also owing to the thermal expansion anisotropy (Lanin and Fedik, 2008).

In the thermo-elastic approach, when materials are subjected to stresses within their elastic range, the resulting total strain in the maximum principal orientation can be calculated in accordance with Equation 1-1. Likewise, thermal stresses are derived from thermal strains, which can be computed as demonstrated in Equation 1-2 (Noda, 2018). Thermal stress resistance (R) then is defined as the ratio of the strength of a material to the thermal stress value, as per Equation 1-3

$$\varepsilon_1 = \frac{1}{E} [\sigma_1 - \nu(\sigma_2 + \sigma_3)] + \alpha \Delta T \quad \text{Equation 1-1}$$

$$\sigma_{\text{thermal}} = 3K\alpha\Delta T \quad \text{Equation 1-2}$$

$$R = \sigma_{\text{tensile}} / \sigma_{\text{thermal}} \quad \text{Equation 1-3}$$

Where E: Young's modulus (GPa), K: bulk modulus (GPa), ν : Poisson's ratio, ε_1 : maximum principal strain, σ_1 : maximum principal stress, $\sigma_2 \sigma_3$: intermediate and minimum principal stress, σ_{tensile} : tensile strength (MPa), σ_{thermal} : thermal stress associated with temperature variation, α : thermal expansion coefficient (1/°C), ΔT : temperature variation (°C), R: thermal stress resistance.

Under stable thermo-mechanical conditions, it is anticipated that R remains above 1. However, this concept has been revised to accommodate mechanical conditions that could either increase the overall stress in the system or lower the strength. The introduction of a new variable, the regime factor (Q), considers factors such as shape, size and thermal conditions, and correlates with the thermal stress resistance concept according to Equation 1-4 (Dauknis et al., 1971).

$$R_e = \Delta T / Q \quad \text{Equation 1-4}$$

The significance of the R_e formulation lies in its consideration of not only the magnitude but also the rate of thermal variations. Consequently, under daily cycles of rock surface temperature, the thermo-mechanical fracturing is anticipated to occur gradually rather than instantaneously. Experimental methodologies have aided researchers in identifying stages of equilibrium and non-equilibrium during crack growth (Hasselman, 1963), predominantly from an energy balance perspective, through the application of this concept. This becomes relevant to investigate thermo-mechanical fatigue, understanding the synchronization between thermal and mechanical response of materials.

1.2.2 Temperature calculations in solids

The transient temperature of a solid (RST) is determined by Equation 1-5, as established by Carslaw and Jaeger (1959). This equation incorporates the notion of conduction (Q_{cond}), which arises from the equilibrium of heat fluxes acting on the outer surface of a solid, predicated on an energy balance principle. This balance involves the concepts illustrated in Figure 1-1.

$$\text{RST}_t = \text{RST}_{t-1} + \left(2 * \frac{Q_{\text{cond},t}}{k_r} \right) \sqrt{\frac{\alpha * \Delta t}{\pi}} \quad \text{Equation 1-5}$$

RST_{t-1} is the rock surface temperature in the previous interval, °K, $Q_{\text{cond},t}$ is the heat exchange under conduction at current time, W/m², k_r is the thermal conductivity of rock, W/mK, α is the thermal diffusivity, m²/s, Δt is the interval of time.

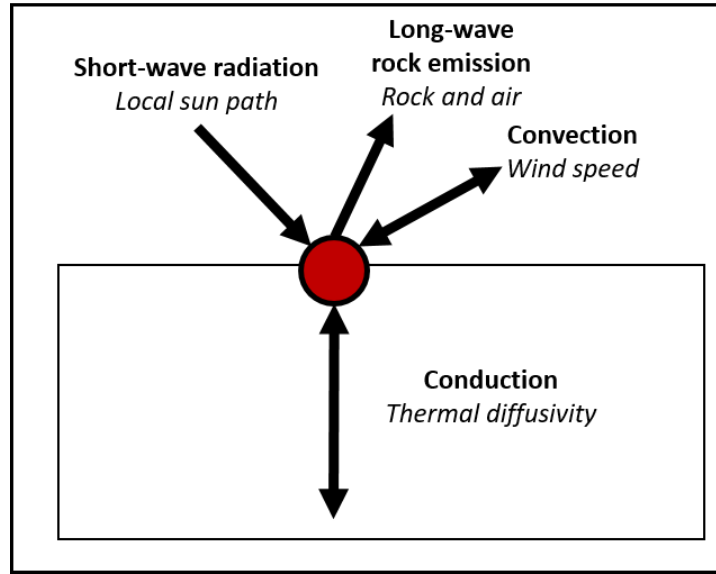


Figure 1-1: Thermal fluxes acting on a surface (single point) for outdoor conditions, simplified with no water.

The general calculation for solids subjected to outdoor conditions (uncontrolled environments) is elaborated as follows:

- a. Short-wave radiation (Q_{rad}) comprises sunbeam radiation (Q_b) and indirect radiation (Q_{ind}) emanating from adjacent surfaces. Given that radiation is typically measured on flat horizontal planes, the measured Q_b necessitates adjustment based on the inclination of the surface under study (Gunzburger and Merrien-Soukatchoff 2011). An approximation of the actual shortwave radiation affecting the rock mass involves considering the impact of Q_b during the local sun hours, primarily due to topographical factors, while disregarding Q_{ind} due to its comparatively low intensity when juxtaposed with Q_b .
- b. Albedo from the surface to its surrounding (Q_{alb}) is quantified as long-wave radiation, computed using Stefan-Boltzmann's law through Equation 1-6.

$$Q_{alb} = \sigma \cdot \epsilon_{emi} \cdot (T^4 - T_{sky}^4) \quad \text{Equation 1-6}$$

Where σ : Stefan-Boltzmann constant ($5.67 \cdot 10^{-8} \text{ W/m}^2\text{K}^4$), ϵ_{emi} : rock emissivity, T_{sky} : temperature of the sky or environment.

- c. Convective process induced by fluids (such as water or air) either steady or flowing around the surface yield a convection heat flux (Q_{conv}). This flux is determined by the temperature differences between the surface and the fluid, multiplied by a convection coefficient (h), as defined in Equation 1-7. When fluid velocities surpass the buoyancy effects in heat exchange, the turbulent nature of convection is mathematically linked to the value of h .

$$Q_{\text{conv}} = h (T_{\text{fluid}} - T_{\text{surface}}) \quad \text{Equation 1-7}$$

Following these formulations, the resultant Q_{cond} to be incorporated into Equation 1-5 is delineated in Equation 1-8 as part of the energy balance.

$$Q_{\text{cond}} = Q_{\text{rad}} - Q_{\text{alb}} + Q_{\text{conv}} \quad \text{Equation 1-8}$$

These equations, underpinned by fundamental principles of heat transfer and energy balance, enable a nuanced understanding of the transient temperature changes experienced on solid surfaces. By integrating thermal considerations with mechanical analyses, a holistic comprehension of thermo-mechanical fatigue can be achieved, thus improving the accuracy of predictions and assessments regarding structural integrity and performance of materials such as rock masses.

1.2.3 Thermo-mechanical fatigue

Thermo-mechanical fatigue refers to a condition wherein temperature and strain fields within a solid material vary simultaneously. This temperature-mechanical strain cycling may not necessarily synchronize (i.e., waveforms of cycles may not align), yet both temperature and strain undergo cyclic fluctuations until the solid (in this case a rock, as per the scope of this research) reaches failure due to fatigue. The ASTM E2368-10 standard outlines the procedure for testing materials under a strain-controlled environment, referred to the situation when mechanical forces will not exceed the elastic limit, and strain result from a change in temperature under free expansion conditions. The total strain experienced during the test (ε_t) is defined as the sum of thermal strain (ε_{th}) and the mechanical strain (ε_m) as per Equation 1-9 and Equation 1-10 (ASTM, 2010).

$$\varepsilon_t = \varepsilon_{th} + \varepsilon_m \quad \text{Equation 1-9}$$

$$\varepsilon_t = \alpha \Delta T + \varepsilon_m \quad \text{Equation 1-10}$$

Where α : thermal expansion coefficient ($1/^\circ\text{C}$), ΔT : temperature variation ($^\circ\text{C}$).

The resulting mechanical strain arises from a blend of elastic and inelastic strains, with the accumulation of inelastic strains, termed damage, occurring in each cycle, ultimately leading to failure. To characterize this damage, additional processes typically come into play, influenced by factors such as temperature range and duration of exposure, including creep and oxidation (Christ, 2013). This concept is illustrated in Figure 1-2, depicting fatigue-driven damage predominantly

occurring at low temperatures (below 100°C) under cycle-dependent conditions, which is the scope of this work.

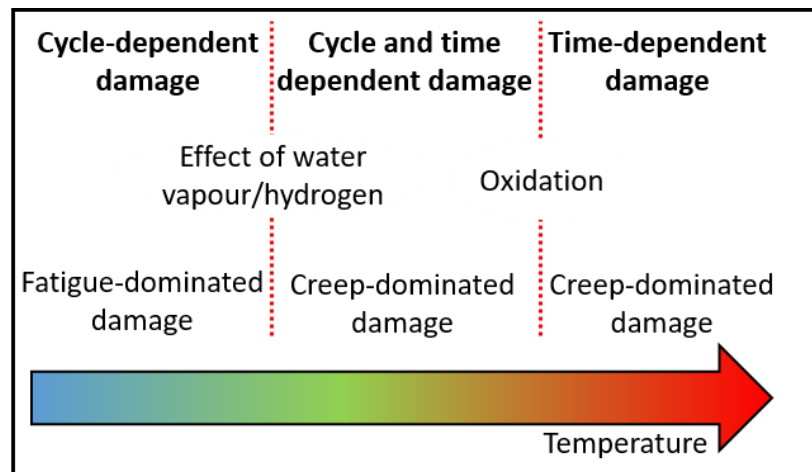


Figure 1-2: Effect of temperature and cycle behaviour on damage mechanism. Modified after Christ (2013).

In environments where strain is not controlled, under cycle-dependent conditions, the stresses induced by thermal fluctuations will similarly vary, encompassing both mechanical and thermal components. This fluctuation, regardless of the waveform it adopts, can be characterized by its amplitude and mean value, referred to as alternating and midrange stresses, respectively (Shingley 2008, citing Goodman 1899). As sketched in Figure 1-3, the midrange stress corresponds to the zeroed point around which the total stress cycle oscillates, whilst the alternating stress represents the total stress magnitude from the midrange to the peak or troughs of the cycle.

Goodman's diagram (1899) elucidates the interplay between these two components in determining material fatigue (Sutherland and Mandell, 2005), offering a failure criterion to predict fatigue-induced failure over cycles. In simpler terms, the Goodman diagram establishes a threshold for stress variations, indicating that high stresses for the same material will vary over a shorter range before reaching failure compared to low stresses, which can fluctuate more extensively. The fatigue limit is proposed to be associated with both the alternating stress (correlated with cycles) and the tensile strength of the material. Theoretically, below this threshold the material can withstand any combination of stresses without failing (Marghitu, 2001). Empirical approaches have demonstrated that this threshold is more accurately conceptualized as a zone rather than a sharp boundary (Shingley, 2008), though the pioneering Goodman's criterion contributes to understanding the fatigue limits.

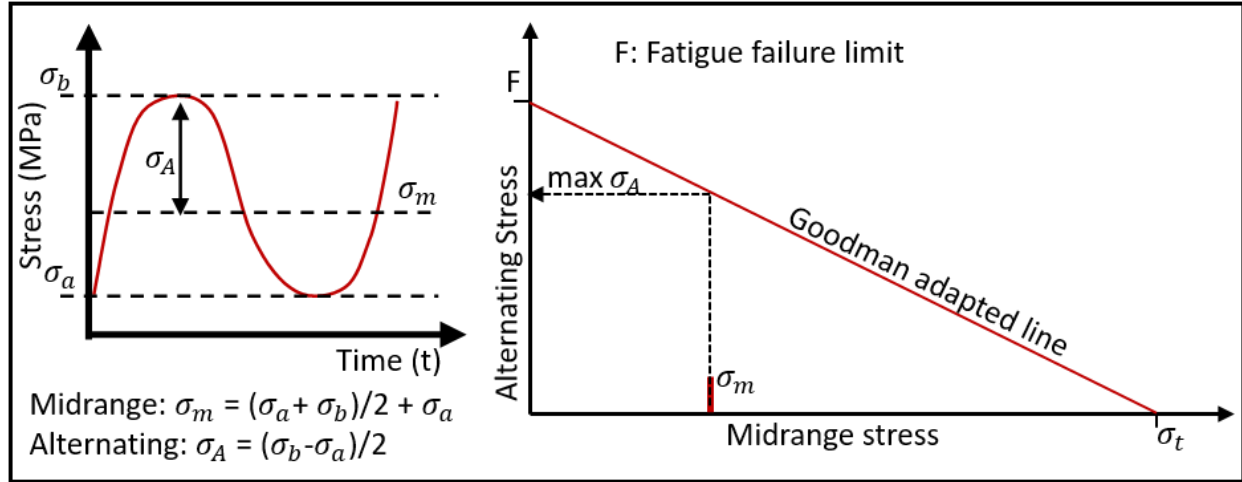


Figure 1-3: Midrange and alternating stresses plot, crucial for assessing the fatigue life of a material. On the left, a schematic depicts stress fluctuation between two values, enabling the calculation of alternating and midrange stresses. On the right, the Goodman's diagram (1899) showcases the fatigue limit, emphasizing the anticipated maximum alternating stress corresponding to a specific midrange stress.

1.3 Thesis Objectives

The objective of this dissertation is to enhance comprehension regarding environmentally driven long-term crack growth mechanisms, presently overlooked in the structural design of civil infrastructures. Specifically, this study investigates the behaviour of rock masses in two distinct sites: the rock slopes within sedimentary formations exposed to hot-desert conditions at the Valley of the Kings (Luxor, Egypt); and horizontal dome-shaped bedrock within metamorphic formations under humid-continental climates situated on Långören Island (Baltic Sea, Finland).

The selection of these two sites is based on their suitability to apply a consistent methodology and analytical model across diverse morphological and climatic settings. Moreover, the documented spontaneous fracturing on Långören Island offers a unique opportunity to observe a site where thermo-mechanical processes had been reported prior to the commencement of this doctoral program. It is important to allude the reader that the focus of this investigation lies on the Valley of the Kings site more than Långören Island, as it allowed for a more extensive collection of data and field campaigns. Nonetheless, the findings from both locations indicate that rock masses are subject to thermo-mechanical fatigue, resulting in varying rates of crack formation.

Thus, the scope of the present investigation is to propose a methodology suitable for addressing thermo-mechanical fatigue in rock masses across various geological, climatic and morphological contexts. To achieve this goal, the specific objectives are outlined as follows:

- a. To undertake a comprehensive analysis of the geological, geotechnical and climatic characteristics of the designated sites, with a particular emphasis on identifying factors that could potentially exacerbate thermo-mechanical fatigue cracking.

Thermo-mechanical fatigue is hypothesized to occur due to a combination of geological, climatic and morphological conditions. However, the specific combination predisposed to fracturing via thermo-mechanical fatigue necessitate thorough investigation. Hence, the aim is to examine the ground conditions of both sites, including literature review, fieldwork observations and monitoring data.

- b. Documentation and evaluation of instrumentation performance and data recording at the site, aiming to identify the factors and conditions likely to induce cyclic thermal deformations and eventual failure of rock masses.

Site investigations were conducted at both locations with the aim of installing a monitoring system capable of measuring the rock mass conditions and response, as a displacement of either fracture networks (Långören Island) or individual fractures (Valley of the Kings). The data collection seeks to quantify the interaction between natural perturbations and the response of the rock mass over time. This entails analyzing overall trends, periodicity and cross-correlations amongst recorded parameters to ascertain the predominant factors in thermo-mechanical fatigue, from a qualitative and quantitative point of view. Additionally, exploratory numerical simulations in a two-dimensional explicit finite-difference continuum, using Itasca FLAC®, was employed to calculate displacements and thermal distributions comparable to empirical data. This allows to prove the conceptual thermo-mechanical action on each site.

- c. Calibration of a three-dimensional finite-difference model to the measured data, coupling thermal and mechanical solutions, in terms of displacements and stresses for the case of the Valley of the Kings.

Enhancing the understanding of the inputs and effects of rock surface temperatures responsible for thermo-mechanical fatigue involves the development of a three-dimensional model in Itasca FLAC3D®. This enables the isolation of thermally driven mechanisms and the determination of the frequency and magnitude of repeated thermal loads, considering both the mechanical freedom of movement and thermal boundary conditions. The transient simulation for the monitored period (i.e., April 2018 to July 2023) provides mechanical (principal) and thermo-mechanical (induced) stresses using a plastic constitutive model, as well as the temperature distribution within the rock masses for specific features in the geometry of the study case. The forecast of ongoing damage

and the anticipation conditions leading to crack extension solely due to thermo-mechanical fatigue are juxtaposed with current observations. This comparative analysis is aimed at discussing potential rock mass instabilities and formulating strategies for hazard mitigations.

- d. Introduce and develop a fracture growth modelling approach for inelastic displacements measured in the Valley of the Kings, involving the applicability of Goodman's diagram (1899) to predict failure resulting from thermo-mechanical fatigue.

Fracture growth is associated with material failure and can be simulated both explicitly and implicitly in 3D models. Modeled stresses, displacements, and strains are essential for defining the capabilities and behaviour of the model. This study discusses the application of Goodman's diagram (1899) for plotting alternating and midrange stresses to account for stress variations caused by thermal perturbations. The hypothesis that thermo-mechanical cycles can induce fatigue is tested using data from the three-dimensional model of the Valley of the Kings, with a focus on stress evolution. Strength limits and associated thresholds, such as crack initiation, are employed to delineate elastic and plastic behaviour under fluctuating thermal conditions.

1.4 Research Significance

This research intends to provide an empirical approach to study thermo-mechanical fatigue of rock masses. It entails conducting two site investigations in distinct geological scenarios, detailing the methodology and instrumentation employed at both sites. Despite previous attempts by various authors to develop criteria for delineating thermo-mechanical fatigue in outdoor conditions, the prevailing approach has been to apply intact rock concepts to rock mass scale, overlooking the presence of discontinuities and the whole stress evolution. Consequently, there is currently no single diagram in the field of engineering geology that integrates thermal and mechanical concepts distinctly within the context of thermo-mechanical fatigue. This gap has persisted partly due to the challenge of isolating a single driven parameter, such as temperature in our research, as well as technological limitations and difficulties in accessing sites.

Hence, the genuine significance of this research resides in conducting a comprehensive analysis of the sites, characterizing the thermal perturbations and the thermo-mechanical response of a rock mass, with a focus on discussing the evolution of the thermal and mechanical stress over the observed period. Although some simplifications were necessary to integrate numerical models, the resulting values are aligned with actual observations. The 3D simulations introduce the concept of a thermo-mechanical fatigue diagram to account for the expected limits of the rock mass given the thermal and mechanical fluctuations individually, yet merged into a singular

diagram. Looking ahead, climate change is expected to bring about more frequent occurrences of higher temperatures. Therefore, since the current conditions of the monitored rock column in the Valley of the Kings, assessing the current impact and proposing criteria to study fracturing are also relevant for the archeological community working in the Theban Mountains.

It is pertinent to note that the Valley of the Kings site holds UNESCO World Heritage status. This research also contributes to its preservation by analyzing stability and providing valuable data, including geotechnical properties and climatic values. Such data are not always readily available to multidisciplinary teams working in the area, due to logistic and inherent restrictions. Our research team was granted permission by the Ministry of Antiquities of Egypt to carry out our plan and data collection, a privilege not commonly granted at such sites.

1.5 Dissertation Outline

To facilitate reading, this dissertation has been structured into eight chapters, encompassing various aspects of the research. Some chapters compile conference articles, while others incorporate published journal articles. Additionally, there are chapters containing unpublished results that address specific objectives of this study.

CHAPTER 2 includes a literature review that explores the concepts of fracturing from the perspective of fracture mechanics. The review delves into the micromechanics of fractures, elucidating subcritical crack growth resulting from environmental conditions. It discusses conditions for static and dynamic loads, whilst also introducing the expressions to analyze loading cycles to address dynamic thermal conditions. Furthermore, the chapter includes an extensive review of thermally-assisted fracturing in near-surface environments, drawing from publications by several authors to compile specific investigations and common findings.

CHAPTER 3 introduces the methodology of the research, detailing the stages to carry out from on-site data collection to numerical model. A flow chart detailing the different stages depicts the sequencing of activities, presenting the framework of this dissertation.

CHAPTER 4 presents the initial approach conducted in Långören Island for the study of spontaneous rock mass fracturing. The research methodology is applied to this site, covering from early monitoring stages to two-dimensional transient numerical models in FLAC®.

CHAPTER 5 focuses on the Valley of the Kings' case, detailing a rock mechanical laboratory program due to the limited information for formal geotechnical and thermal intact rock inputs in the

area. The chapter also describes the geology of the Theban Mountains and the specific rock units present in the area, as well as the archeological context.

CHAPTER 6 summarizes three years of site investigation (2018–2021), presenting the morphological conditions and the collected data. The data undergo comparative analysis with other sources before being inputted into a two-dimensional elastic thermo-mechanical numerical model in FLAC®. The chapter serves as a proof of concept for thermally assisted deformations in rock masses.

CHAPTER 7 introduces the construction and analysis of a three-dimensional numerical model in FLAC3D®, using dynamic thermal inputs. The chapter encompasses the five years of site investigation (2018–2023), with the numerical model implemented under elastic thermo-mechanical conditions and an initial calibration for 12 months only. A sensitivity analysis for calibration of the model is discussed for a year period of monitored data, from a mechanical, thermal and thermo-mechanical perspective.

CHAPTER 8 discusses the full time-series of measured data, describing the elastic and inelastic displacements, i.e., reversible and irreversible displacements. Strategies are formulated to match the fracture opening trend along 6 years, with nearly 100 models simulated varying inputs and model conditions, aiming to generate failure at specific feature and the increasing trend of displacements. The resulting deviatoric stresses are analysed utilizing the Goodman's diagram (1899) with a focus on proposing a conceptual criterion for thermo-mechanical fatigue limits.

CHAPTER 9 presents the main conclusions of the overall investigation.

A reference list and appendices are included at the end of the dissertation. Extra data and FLAC3D® scripts are also included as part of the research's contribution.

CHAPTER 2 LITERATURE REVIEW

2.1 Theory and Empirical Approaches

2.1.1 Fracture Mechanics and Subcritical Crack Growth Conceptualization

Fracture mechanics in geological materials has traditionally been approached from a macroscopic engineering standpoint. While this perspective suffices in certain instances, for a comprehensive understanding of brittle fracture mechanisms, the insights offered by micromechanics prove invaluable. This approach elucidates the influence of rock components heterogeneity (e.g., voids, minerals, residual strain) and their interaction with environmental factors (e.g., gravity, weathering) on crack propagation, transitioning from a microscopic to a macroscopic scale.

In the framework of linear fracture mechanics, crack opening is analyzed according to Griffith's mode of cracking (1920), with particular emphasis on stresses and strains in the vicinity of the crack tips, as depicted in Figure 2-1. While the author formally introduced criteria to determine the energy necessary for fracture extension, this approach predominantly disregarded inelastic terms associated with fracturing, thereby skewing results towards pure surface energy considerations, which underestimate the required threshold. Notably, these calculations were confined to the elastic regime, hence theoretically reversible (Gross and Seelig, 2006). To address this limitation, Irwin (1957) extended the analysis into the elastic-plastic region, specifically focusing on the area immediately behind the crack tip, known as the K-dominated region. This expansion accounted for the strain energies absorbed and dissipated during loading, yielding a physical measure, the stress intensity factor (K-factor), as a key parameter characterizing energy loading in the crack-tip field.

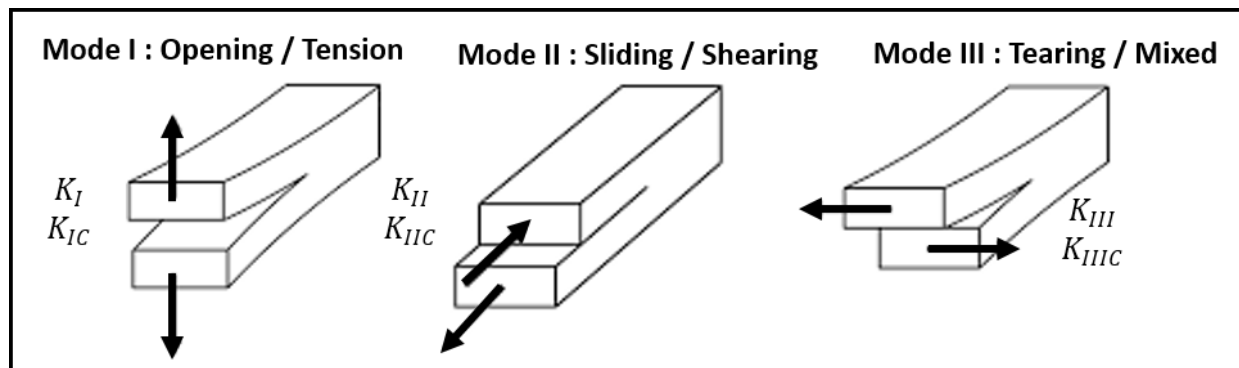


Figure 2-1: Griffith's modes of failure correspond to three distinct types of crack extension, each linked with Irwin's stress intensity factor.

Since Irwin's seminal publication in 1957, the stress intensity factor (K-factor) has garnered significant attention within the scientific and engineering community, serving as a critical

parameter delineating material fracture behaviour when the fracture toughness is surpassed (K_{Ic} , denoting critical failure limit, determined experimentally via ISRM1988 and ISRM1995). Correspondingly, K-factors and K_{Ic} values are computed for all three modes of failure proposed by Griffith (1920), denoted with subscripts I, II or III, corresponding to different types of crack extension.

In contrast to conventional strength limit analysis, the K-factor quantifies the energy required to induce fracture, while strength denotes a materials' resistance to complete failure, rendering these concepts mutually exclusive (Ritchie, 2011). For instance, ductile materials capable of withstanding larger strains at yielding exhibit higher K_{Ic} values (e.g., engineering metals or polymers), even if their ultimate strength is orders of magnitude lower than that of brittle materials, which typically have lower K_{Ic} values (e.g., oxide glasses, engineering ceramics, rocks). The extensive adoption of K-factors depends on their ability to integrate analytical, numerical, and experimental methodologies for predicting crack propagation, accounting for both the magnitude and orientation of individual and aggregated flaws. Nonetheless, this method imposes constraints on the geometry, characteristics, and velocity of crack propagation processes (Lazarus, 2003).

One significant application of these principles involves investigating subcritical crack growth under varying environmental conditions, such as temperature and relative humidity. This process has been extensively examined and elucidated through the correlation between the stress intensity factor (K-factor) and energy, initially proposed in the pioneering work on static fatigue in glass by Charles (1958). Subsequent research by Wiederhorn and Bolz (1970) further advanced this understanding, experimentally suggesting that the rate of crack growth, known as crack velocity, in corrosive environments is influenced by the temperature and activation energy of materials, which are interconnected with K_I and K_{Ic} . This dependency has been empirically studied, aiming to elucidate the variations of the stress regime during the cracking process under monotonic loads, known as static fatigue. Several authors have demonstrated that exponential growth rate of cracks can exhibit a linear relationship with temperature and relative humidity (e.g. Li et al. 2019, Voigtländer et al. 2018, Chen et al. 2017, Nara et al. 2017, Bergsaker et al. 2016, Hu and Hueckel 2014, Brantut et al. 2013, Rostom et al. 2013, Holder et al. 2001).

2.1.2 Subcritical Crack Growth Under Static Loads

In the realm of rock engineering, Atkinson (1982) delved into the correlation between crack velocity and K_I (specifically the ratio K_I/K_{Ic}) across various rock types, including quartz, quartzite, calcite and granitic rocks. This relationship was established through torsion tests conducted at room temperature in water. Atkinson concluded that at lower values of K_I , crack velocity remains

independent of the stress state of the material but is influenced by factors such as temperature, pressure, corrosion activity, and chemical solubility, as observed experimentally and illustrated in Figure 2-2.

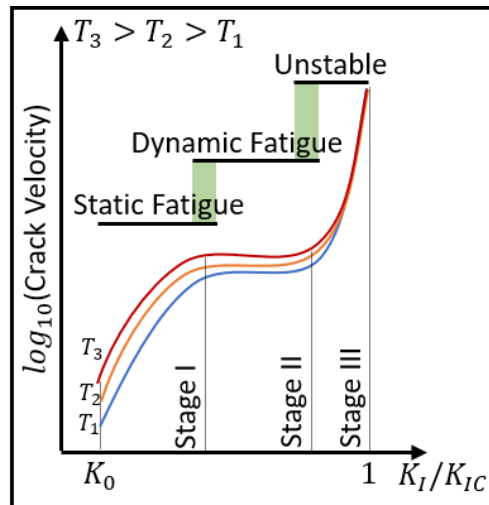


Figure 2-2: Static and dynamic fatigue, showing the velocity of crack propagation at varying temperature with fluctuations in the ratio of stress intensity (K_I) to fracture toughness (K_{IC}). The figure annotates different stages, with green regions indicating conceptual overlaps between these stages.

In uncontrolled conditions, this phenomenon can indeed be associated with the weathering process of rocks (e.g., Schultz 2000, White and Brantley 2003). However, it is worth noting that weathering primarily involves time-dependent damage rather than cyclic-dependent damage, and typically entails chemical reactions. For instance, Freiman (1984) explored the impact of chemical reactions on stress-assisted crack propagation, highlighting a region where mechanical stress leading to brittle failure competes with other mechanisms such as stress corrosion, dissolution, diffusion, ion-exchange and microplasticity (Potyondy 2007). This region, influenced by the composition and structure of materials, may persist before mechanical stress initiates macroscopic fracturing processes (Swanson, 1984).

Additionally, Lajtai and Bielus (1986, references therein) investigated static fatigue based on studies from the 1970s, conducting tests on granite with water. The authors concluded that the exponential rates of crack velocity tend to decrease when transitioning from dry to wet environmental conditions, while K_I increases. Nara et al. (2013) also investigated the influence of water through tests conducted on igneous rocks (andesite and granite), in double torsion tests conducted at temperatures ranging from 11°C to 55°C and wide relative humidity range (2% to 81%), along with some tests conducted in water (pH 5 to 8). The authors conclude that crack velocity is slower in water compared to air (at various relative humidity levels), and decreases with

rising temperatures. At low temperatures, subcritical growth does not occur, with fracturing primarily driven by chemical interactions and minimal influence of stress. Atkinson (1984) previously suggested that water's influence could lead to changes in the stress tensor, alterations in the mechanical properties of a pre-existing fluid (at the crack tip), loss of integrity (resulting in macrocracks), or triggering of chemical reactions. However, Atkinson's tests did not account for the degree of saturation and permeability of the solid/liquid phase, which could potentially induce fracturing. Balancing these factors in water tests over short durations is challenging (Laubach et al., 2019).

2.1.3 Subcritical Crack Growth Under Dynamic Loads

Under transient conditions, brittle materials may undergo dynamic fatigue crack growth when subjected to cyclic loading. During phases of void separation and relaxation (cycles), cracks at the edge of material defects can experience sustained unstable propagation, even at lower levels of ultimate strength. However, geotechnical research on the kinetics of dynamic fatigue cracking is limited compared to static fatigue (Costin et al. 1981, Li et al. 1992, Erarslan and Williams 2012, Le et al. 2014), with most studies in rocks focusing on the effects on strength and fracture toughness (K_{IC}) (Gatelier et al. 2002, Erarslan and Williams 2012). Consequently, much of our understanding in this area stems from mechanical engineering studies of ductile materials.

Paris and Erdogan (1963) formulated an expression to determine the crack growth rate due to the number of fully reversed cycles (i.e., cycles of the same magnitude of stress in compression and tension) and materials properties, exponentially linked to the K -factor of ductile materials, known as Paris' law. Experimental work has demonstrated the applicability of Paris' law to brittle materials (e.g., ceramics, concrete); however, the exponential rate is significantly higher than in ductile materials (Ritchie, 1999). As depicted in Figure 2-3, when a cyclic load acts on a material, its range of stress intensity variation (ΔK) will determine the extension of the crack (a) on each loading cyclic (N) according to Paris' law during fully reversed cycles. Since deviations from real observations and analytical results come from a broad spectrum of materials, the test data are plotted in a logarithmic scale with Paris' law parameters C and m , to illustrate the linear relationship and hence describing the velocity of crack growth.

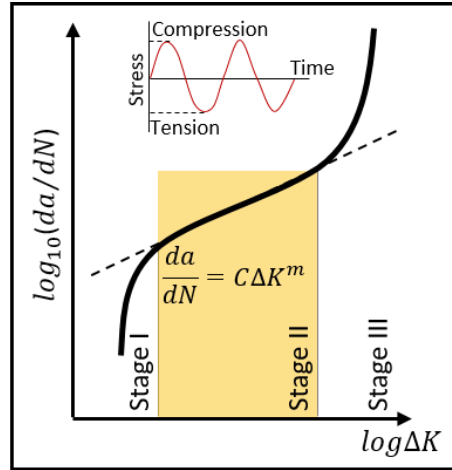


Figure 2-3: Paris-Erdogan diagram for fully reversible loading cycles, which is applicable in Stage II fracture toughness behaviour. Vertical axis as logarithm scale of crack length, or extension “a”, as a result of number of cycles “N”. The dashed line represents the best linear fit to determine the Paris’ law constants C and m.

In the fatigue life of material, Paris’ law disregards the crack initiation phase noted as Stage I, focusing solely on the propagation phase (Stage II), and limiting the consideration of transient effects unless the fast crack propagation phase (unstable, Stage III) initiates, which depends on previous cycles. Typically, the fatigue life is categorized into low, intermediate, and high cycles based on the number of cycles endured by materials rather than the magnitude of loading. For instance, in steels, the low cycle region spans up to 10^3 cycles, while the high cycle region begins from 10^6 cycles. The intermediate region falls within the boundaries of low and high cycles (Shigley, 2011).

Moreover, Paris’ law tends to underestimate the extension of short cracks, satisfying specific regimes of either long cracks or low loads where the crack growth rate per cycle is lower than 10^4 mm/cycle (Pugno et al., 2006, Ciavarella et al. 2018, Carpinteri & Montagnoli 2019). Consequently, numerous fatigue rate equations have been proposed in the literature to reconcile empirical observations with analytical results. However, no perfect model exists to quantify this process due to the assumption of material isotropy, leading most approaches to be stochastic rather than deterministic (e.g. McEvily and Groeger 1977, Allen et al. 1988, Chow and Lu 1991, Ritchie 1999, Lesiuk 2019).

2.1.4 Subcritical Crack Growth Under Dynamic Thermal Conditions

Increasing attention has been directed towards fatigue crack growth induced by thermo-mechanical loading (TM), owing to the significant damage to materials resulting from cyclic fluctuations in operational and environmental conditions, with a focus on the analysis of material lifespan. As investigated for serviceability assessment of ductile materials through experimental

work (Bill et al. 1984, Toumi et al. 1998, Maillot et al. 2005, Ko and Lee 2020) and case studies (Ancelet et al. 2007, Le and Gardin 2010, Molent and Jones 2016), the response of materials under isothermal low-cycle fatigue is deemed more critical than the maximum monotonic load obtained at operational temperatures. Additional challenges arise when cycles vary randomly or are scarcely defined (referred to as unknown waveform), due to phasing effects (e.g., in-phase/same-frequency, out-phase/same-frequency, different-frequency), as illustrated in Figure 2-4. For instance, the study of thermo-mechanical fatigue of rock masses can be linked to fluctuation in temperature, seismic activity, mineral hydration, creep, hydraulic pressure, that will impact the stress tensor, leading to fluctuation in the stress intensity state around existing cracks. These perturbations can act cyclically with known amplitude and frequency, adding the challenge of defining a unique integrated loading function.

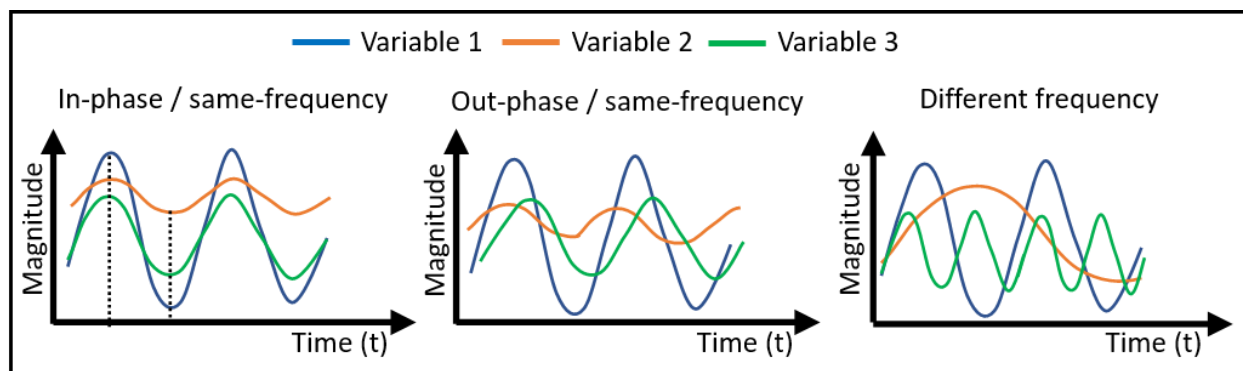


Figure 2-4: An overview of different type of loads acting on a solid, or rock mass, at the same time of exposure. As they may be different in nature, the amplitude and frequency do not match each other.

To combine the effects of the individual perturbations, the application of the total damage equation of Palmgren-Miner (Palmgren 1924, Miner 1945) aids in forecasting the lifespan of engineering materials as a result of the combined effects from cycles with different frequencies and amplitudes. However, analytical models for temperature fluctuations predominantly cover ductile and semi-ductile behavioural materials (Taira 1962, Sidey and Coffin 1979, Coffin 1976, Manson et al. 1971, Halford and Saltsman 1988). Most of these models attempt to elucidate the interaction between creep and fatigue during fully reversed cycles, raising the questions about their applicability during the high-temperature low-cycle range (Christ, 2013).

In brittle behaviour, as commonly exhibited by geological materials, experimental findings suggest that crack growth rates are higher in thermo-mechanical (TM) fatigue induced by temperature cycles compared to isothermal mechanical fatigue. Regardless of the loading type, similar coalescence patterns are observed (Ko and Lee 2020, Royer-Carfagni and Salvatore 2000, Ritchie and Dauskardt 1991). Thermo-mechanical fatigue leads to crack extension due to thermal-

strain rates associated with free expansion at temperature fluctuation, resulting in material property degradation and rapid stress generation, which can surpass tensile strengths more readily than in ductile materials due to shorter deformations (Arabzadeh and Guler 2019). For instance, TM fatigue in concrete pavements is typically classified as low-temperature cycles (fluctuations lower than 20°C) as a result of day-night variations, leading to transient thermal strain fluctuations that gradually vary with depth, evolving into a stress gradient (Dore and Zubeck 2009, Carpenter 1977).

Evaluation of concrete behaviour under different laboratory conditions have been carried out by several authors, concluding that effect of environmental aging must be considered to determine a material's response to TM fatigue (Shafiee et al. 2017, Zhu et al. 2017, Marasteanu et al. 2012, Epps 1999, Jackson and Vinson 1996). On-site measurements of anisotropic deformations (horizontal and vertical) have demonstrated significant differences in TM fatigue between orthogonal orientations and during seasonal variations (waveform), underscoring the importance of accounting for thermal-induced strains and assessing asphalt concrete under transverse isotropic deformation, with indirect implications for resulting ΔK_I (Islam and Tarefder 2014, Al-Qadi 2005, Bayat et al. 2020).

Indeed, thermal strain can influence the elements near the crack-tip, thus, under TM fatigue, K_I becomes a function of temperature and load. Menouillard (2010) demonstrated that increasing temperature along the crack axis elevates K_I . The author developed a numerical model of mixed-mode fracture (K_I and K_{II}) with temperature dependence, assuming a steady-state temperature variation across a solid (plane strain). The energy release is described using the J-integral method, providing solutions in terms of K-factor and deformations. The J-integral offers an alternative approach to Griffith or Irwin's theories, introduced by Rice (1968) to determine the strain field around cracks and notches in both linear elastic isotropic and non-linear inelastic anisotropic materials. Other non-isothermal fatigue models for continuous damage have been proposed based on either uncorrelated fracture mechanics result or the use of constants lacking physical justification from experimental work, only evident in mathematical derivations (Carrara et al. 2020, Boldrini et al. 2016, Chow and Lu 1991, Dowling 1976).

2.2 Generalized Fatigue Failure

Thermo-mechanical fatigue failure typically arises from fluctuating temperatures, inducing thermal stresses capable of causing material failure even at stresses below its strength. This integrated action connects macro-scale processes to fracture extension, necessitating the decoupling of thermo-mechanical effects to isolate thermal fluctuations' impact. For example, Kant et al. (2017)

investigated K_I variation in rocks during drilling, considering temperature fluctuations (mainly incremental due to drilling) and fluid pressure to describe stress intensity numerically. However, this work primarily focuses on repeated thermal loads applied to rock surfaces, exhibiting low-frequency and low-amplitude load dynamics compared to engineering materials (See section 2.1.3 and 2.1.4). Consequently, resulting crack growth behaviour tends to be non-linear, prompting the relevance of Goodman's empirical approach (1899) to depict the relationship between midrange and alternating stress in predicting fatigue limits and introducing a generalized failure model.

The Goodman diagram serves to establish the maximum and minimum permissible cyclic stress levels that a material can withstand (see section 1.2.3). While in ductile materials, these stress limits are typically defined by the endurance and yielding stress thresholds, pinpointing equivalent parameters in brittle materials proves challenging. This difficulty arises from the short duration (low-cycles) of fatigue failure tests. It is worthwhile to mention that the current research primarily focuses on the macro to field scale behaviour of intact rock masses, where compressive loads are dominant, despite tensile behaviour governing at the microscopic level. Fundamental relationships to predict failure have been studied empirically for compressive and tensile regions at different alternating and midrange stress values, introduced in Figure 2-5a. The figure shows the enclosure in which a material subjected to fluctuating stresses will not fail, yet the failure is reached at stress threshold below the ultimate strength. Note that tension is positive and compression is negative. Figure 2-5b shows hypothetical tests in materials subjected to compression and tension. For the tensile stress regime, materials can fail at smaller ratios of stress to tensile strength than in a compressive regime. Empirical approaches have derived a series of failure criteria, as shown in Figure 2-5c. Goodman (1899) proposed a straight-line failure criterion, which is more conservative in terms of observed alternating stress values than Gerber's (1874) ellipsoidal-cap criterion, which it limits most of empirical data. Other models propose the use of yielding points to limit the midrange magnitude, such as Soderberg (1930).

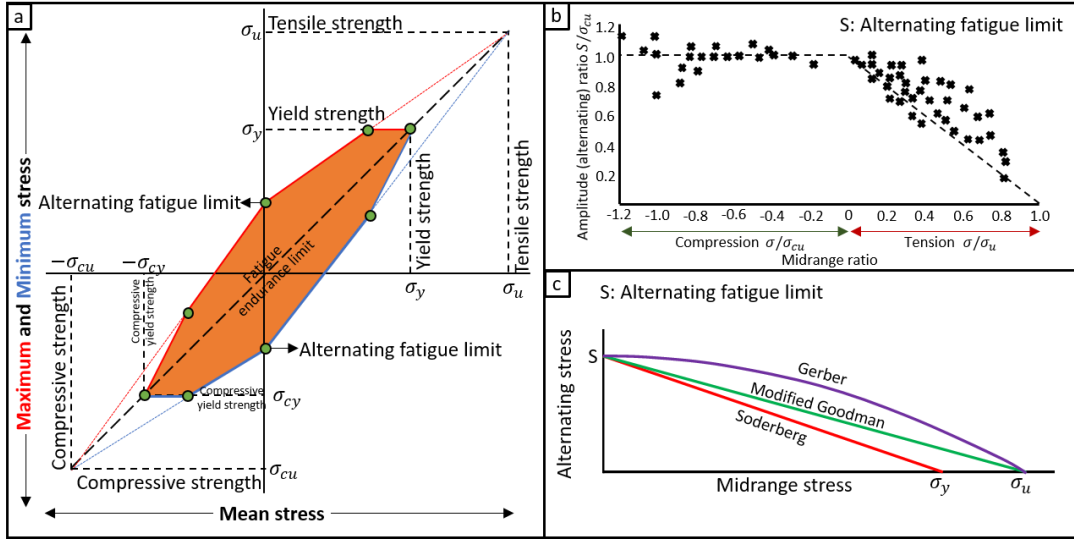


Figure 2-5: Stress fluctuation plots for a) Goodman generalized for tension and compression range of stress. Sign convention as negative for compression and positive for tension (following Mechanical Engineering nomenclature). Also, b) experimental work to quantify fatigue limits in compression and tension (Shigley 2011, references therein), and c) failure criteria for fatigue life of a material using a plot for midrange and alternating stresses. Capping curves proposed by the classic approaches from Goodman (1899), Gerber (1874) and Soderberg (1930). Figure modified after Shigley (2011).

2.3 Thermally Assisted Fracturing in Near Surface Environments

In broad terms, subcritical cracking processes can be identified in the literature by various terms, including environmentally assisted cracking, stress corrosion, time-dependent crack growth, progressive failure, micro-cracking, static fatigue or thermo-mechanical fatigue (Merrien-Soukatchoff and Gasc-Barbier 2023, Eppes and Keanini 2017). Nonetheless, the underlying mechanisms distinguish between pure thermally induced stresses that trigger cracking. Experimental studies aimed at investigating subcritical cracking processes in intact rock date back to the 1980s (Atkinson 1982, Meredith and Atkinson 1983). Since then, the primary findings indicate that the subcritical cracking process does not conform to equilibrium laws but instead follows kinetic laws, exhibiting a dependency on stress, geometry and the condition of the rock (Eppes and Keanini 2017); akin to the empirical approaches for materials outlined in the previous sections.

Attempts have been made to scale thermo-mechanical (TM) fatigue crack growth concepts to rock engineering principles, both empirically and analytically, albeit with limited success (Bazant 1991, Let et al. 2014, Merrien-Soukatchoff and Gasc-Barbier 2023). Hall and Thorn (2014) argue that thermally induced stresses might precipitate TM fatigue failure in rock masses, owing to cyclic straining and progressive damage. This fatigue process has been attributed to temperature fluctuations affecting both the rock mass and intact rock walls of cracks, resulting in the expansion

and contraction of minerals, thereby promoting crack growth from pre-existing micro-cracks such as crystal boundaries or cleavage planes. These changes inherently modify the intact rock properties such as strength and stiffness (Gasc-Barbier et al. 2014, Villarraga et al. 2021).

The contributing factors to crack growth due to TM fatigue remain unclear, especially in near-surface bedrock geological settings. Specifically, there is a lack of precise definition regarding the temperature range for crack formation, encompassing variables such as duration of sunlight exposure and rates of temperature change. Hall and Thorn (2014) identify key prerequisites for cracking induced by adverse weather conditions, highlighting (1) the existing fracture density relative to the stress state of the rock mass, (2) the additional loads resulting from thermally induced stresses, and (3) the energy absorbed by the rock surface due to solar radiation, which includes factors like frequency, duration of exposure and resultant rock surface temperature, all of which influence the probability of cracking.

At the macro-scale, research has honed in on the behaviour of boulders within outdoor environments, particularly regarding the influence of added energy on crack development (Eppes, 2017). McFadden et al. (2011) scrutinized the effects of solar radiation on fracture formation in boulders across desert regions of the United States, proposing that fractures stem from tensile stresses induced by a radial temperature gradient following the sun's trajectory throughout the day. Their study employed statistical analyses to correlate joint orientations on boulders with cyclic fatigue of rocks in specific orientations. Similarly, Lamp (2017) delved into boulder fracturing in Antarctica, investigating the collective impacts of sunlight, wind, and temperature on rock weathering and spalling. Their findings highlighted an increase in rock porosity attributed to crack propagation, which subsequently led to a reduction in fracture toughness within alteration rinds. Eppes and Keanini (2017) developed a conceptual model elucidating climate-dependent subcritical cracking of rocks, focusing on the breaking of bonds in crack tips under stress levels below the critical rock strength. Their research underscored how incremental rises in relative humidity exponentially accelerate cyclic fatigue, modelled according to Paris' law. However, the challenge lies in distinguishing between coupled weathering processes and TM fatigue due to limitations in sample size and the rapid pace of cracking phenomena.

This complexity poses significant challenges to the rock mechanics community, necessitating the identification of TM fatigue-related occurrences and the implementation of advanced monitoring systems to comprehend the spontaneous response of rock masses to climatic influences. In jointed rock masses, the thermo-mechanical cycles can induce the initiation and propagation of cracks along pre-existing fractures (i.e., joints), and contribute to the formation of new fractures.

This raises concerns regarding the reduction in strength and stiffness reduction, the elevation of permeability values and environmental degradation (Aldred et al., 2016).

Several authors have conducted monitoring studies at the rock mass scale to examine the correlation between rock surface temperature fluctuations and deformation in rock masses. Technological advancements have facilitated the use of integrated monitoring systems at low cost, easy maintenance and manageable dimensions. Consequently, monitoring efforts focused on rock masses have increased over the past decades worldwide, contributing to a deeper understanding of the conditions to fracturing.

Some authors have concentrated on monitoring displacements only (e.g., Krahenbuhl 2004, Watson et al. 2004, Gunzburger et al. 2004, Bievre et al. 2018), while others have sought to comprehend the temperature distribution within the rock mass (e.g., Gruber et al. 2004, Clement et al. 2008, McKay et al. 2009, Gunzburger and Merrien-Soukatchoff 2011, Messenzehl and Dikau 2017, Zhao et al. 2021, Racek et al. 2021, Virely et al. 2021, Brytenbach 2022). Non-invasive techniques such as infrared thermographic surveys (e.g., Chen 2017, Frodella et al. 2017, Coggan et al. 2016, Fiorucci et al. 2018, Guerin et al. 2019, Grechi et al. 2021) and microseismic monitoring (e.g., Senfaute et al. 2009, Rantanen 2016, Bottelin et al. 2017, Valentin et al. 2017, Colombero et al. 2021b, Grechi et al. 2023) have also been deployed for this purpose.

However, the parametric analysis, remains confined to specific locations and environments. Authors frequently neglect to provide a prototype model to clarify the observed relationships. In some instances, the monitoring duration may be inadequate to gain a comprehensive understanding of the behaviour of the rock mass as a whole. Additionally, the presence of joints and their opening-closing cycles due to thermal dilation cycles is commonly overlooked in the analysis (Grechi 2021, Merrien-Soukatchoff and Gasc-Barbier 2023). Table 2-1 presents an overview of worldwide monitoring efforts concerning thermo-mechanical fatigue conducted by various research teams, excluding any studies from our own research team. The most recent publication, as of the date of publication of this manuscript, is from 2021 (Gasc-Barbier et al., 2021), subsequently complemented by Merrien-Soukatchoff and Gasc-Barbier (2023). It is noteworthy that the onset of the COVID-19 pandemic from 2020 to 2023 significantly impeded research activities worldwide, particularly those conducted in remote locations. This led to a deceleration in the publication of research in this field, with a shift in priorities towards more numerical analysis of existing data rather than on-site instrumentation and monitoring in new areas.

Table 2-1: List of on-site investigations researches published to date worldwide, including thermal (T) and thermo-mechanical (TM) models. Morphology is detailed to differentiate between tall cliffs, landslides, rock arches, and shallow rock surfaces in general. The abbreviations used are as follows: AT air temperature, RT rock temperature, T temperature, D displacement, GI ground investigation, M mechanical, 2D two-dimensional, 1D uni-dimensional, RH relative humidity, IRT infrared thermography.

Reference	Location	Rock Type	Morphology	Site Investigation	On-site data	Numerical Model	Main Conclusions
Ishikawa et al. (2004)	Japan, Daisetsu Mountains	Andesite	SW slope, vertical and horizontal joint network	During September 1997: Crack-meter and rock temperature were measured every 10 min.	ΔAT 0°C to 25°C along a month rate of crack aperture -0.02 to 0.02 (mm/hr), with large displacement during rainfall	Theoretical TM-2D of spalled walls	Temp. cycles can lead to fatigue and brittle failure, since normal stress at crack tip exceeds fracture toughness (already weakened)
Watson et al. (2004)	Canada, Revelstoke dam	Granodiorite (foliated) on gneiss/schist sequence	Landslide of 300m in height with a weathered upper layer (60m).	Extensometer, RT sensor, piezometers	ΔAT -25°C to 35°C along year. D in order of 0.5-1.3 mm/year, and GWL varies about 15m yearly.	UDEC, M-2D Theoretical wedging mechanism	Thermal cycles are linked to displacements recorded at rock surface which lead to progressive failure of the upper weathered layer.
Grief et al. (2006)	Japan, Bitchu-Matsuyama castle	Granite, very jointed	Rock slope, 30m in height, dipping 65°-80°	For 3 years: extensometers (x3) and crack gauges (x3), tiltmeter, temp. sensors (rock and air) and rain gauge.	Large D (1-10 mm) related to gravitational processes mainly. ΔAT 0°C to 35°C across year, with max. daily ΔT 10°C. Prec. are quite frequent, up to 60mm/day. Short D (<1mm) linked to inverse trends of T.	Laboratory scale, M-2D to determine mode of failure	Due to one section performed large displacements, the focus of the analysis was on explaining the mode of failure by statics approaches, and no analysis of thermal cycles is derived from this research, although data were recorded.
Gunzburger et al. (2005)	France, Southern Alps	Gneis (Variscan)	Slope of 50m in height and dipping 45°SE	For 2 days in summer and 1 day in spring: Total station with a network of 16 prisms WST placed <i>near</i> of site.	ΔD 0.2mm/day at $\Delta 15^\circ C$ (rock surface temp.) GI is continued by Senfaute et al. (2007).	RESOBLOCK, M-2D Theo. TM-2D, triangular-block	Temp. variations may assist slope failure, although long-term GI is needed. Theoretical model helps understand plastic deformations of joints.
Senfaute et al. (2007)	France, Southern Alps	Gneis (Variscan)	Slope of 50m in height and dipping 45°SE	For 3 years: 6 tiltmeters, temp. and rainfall are measured close to tiltmeters. 4 x 1D geophone and 1 x 3D accelerometer.	About 2000 seismic events of high frequency (>100Hz) and short duration were observed when changing in temp ($\Delta 15^\circ C$) and displacements.	RESOBLOCK, M-2D	Temp. variations assist slope displacements, however no info about rates and change magnitude is provided.
Vlcko et al. (2009)	Slovakia, several locations	Metamorphic sedimentary, quaternary	Hilly land and highlands of 350-700 m.a.s.l.	20 years of exploration in 5 Heritage sites: crack-meters and WST.	ΔAT -5°C to 40°C along year, max. daily $\Delta 20^\circ C$. ΔD <1mm yearly, usually horizontal D the largest.	UDEC, M-2D	Temp. cycles across Slovakia is linked to ΔD , at rates possibly related to rock types, yet unclear.

Table 2-1:Table continuation.

Reference	Location	Rock Type	Morphology	Site Investigation	On-site data	Numerical Model	Main Conclusions
Mufundirwa et al. (2011)	Japan, Iwate	“Chert” blocks highly jointed	Rock slope, dipping >65°SW	For 767 days, 6 crack-meters and WST.	ΔAT -5°C to 23°C along year, daily RH of 50%-100%, D ranges -0.4 to 0.7 mm.	TM-2D in rock surface of 5x5m	Thermal cycles contribute to brittle failure, increasing stress concentration at crack tip, and performing inverse cycles with measured displacements.
Gischig et al. (2011)	Switzerland Randa (Valais)	Gneiss (orthogneiss, paragneiss)	Translational landslide, 500m in height at 50°	From 2004 to 2008: Extensometer, inclinometer, temperature sensor cased in borehole.	ΔAT -10°C to 15°C along year. D rates of 10 mm/year. Precipitation up to 90mm/day. Melting processes conditioning inclinations and accelerations	UDEC, TM-2D	Progressive irreversible deformation is triggered by thermal cycles, due to critically stressed discontinuities. TM effects is more effective in more competent rock mass.
Bakun-Manzor et al. (2013)	Israel, Masada National park	Dolomite, limestone	Block displacement from steep cliffs	For 25 months, extensometers, RT, AT and RH sensors and seismic activity	ΔAT 16°C to 36°C along year, max. daily $\Delta 25^\circ C$. RH moderate from 35% to 80%. D ranging -0.2 to 0.2 mm, with inverse trends to T.	Theoretical TM-2D with wedging mechanisms	ΔD linked to ΔAT . Model based on Gunzburger et al. (2005) “ <i>triangular-block</i> ” model. Compared to seismic forces, previous D of 200mm is more likely to have been thermally induced.
do Amaral Vargas et al. (2013)	Brazil, Rio de Janeiro	Fine grained gneiss and coarse granite	Abandoned quarries with slopes up to 30m	The authors document slope failure due to temperature variations around Rio de Janeiro city (allegedly).	Scale tests to describe the effect of temperature in cracking was conducted in 30x30x20cm blocks at outdoor conditions, with a WST and recording RT	ABAQUS, Physical test is modelled numerically	Evidences of thermal cycles and slope failure are collected qualitatively. Tests in rock blocks help understanding effect of local weather in creating cracks
Botellin et al. (2013)	France, Vercors Massif	Marly limestone	Rock column 30m height, 15m wide and 5m thick (1000m ³)	For 29 months: 3-C seismometers, env. data collected from WST at 3.2km southwest.	ΔAT -9°C to 20°C along year, max. $\Delta 10^\circ C$ during day. Higher vibrations in winter, about 5 times than other seasons.	COMSOL, TM-2D	Freeze and thaw processes lead to changes in vibrations. Temp. has an inverse trend to vibrations with a delay of 3 months, possibly due to thermal expansion.
Vlcko et al. (2014)	Czech Republic, Bohemian Switzerland	Sandstone	Rock arch, min. tie beam thickness 2.5m, span 26.5m	For 3 years: Temp. sensors (x8) Pt1000 within rock mass. D are recorded (no info).	ΔAT -5°C to 25°C along year, max. $\Delta 5^\circ C$ during day. No info of displ. is reported.	UDEC, TM-2D	Temp. oscillations produce changes in stresses due to expansion and contraction, leading to reversible displacements.

Table 2-1:Table continuation.

Reference	Location	Rock Type	Morphology	Site Investigation	On-site data	Numerical Model	Main Conclusions
Collins and Stock (2016)	United States, California	Granodiorite (exfoliation sheet)	Rock slope is 500m in height, studied slab is 19m tall by 4m width, and 10cm thick	For 39 months: crack meters, LiDAR scan surveys. RT, RH, and light sensors on rock surface.	ΔRT from 10°C to 37°C during summer, with $\Delta D < 0.1\text{mm/day}$, and progressive crack aperture of 1mm/year.	Theoretical, TM-2D of exfoliated geometry and stress at crack tip.	Bedrock are dynamically affected by temperature cycles which can increase the stress intensity to trigger cumulative of opening of fractures.
Taboada et al. (2017)	France, Larzac	Dolostone	Vertical cliffs with rock columns of 50m height.	During 30 months: crack meters and temperature sensors.	During annual cycles, column moves at rate of 1.2 mm. Changes in angle of displacement vector throughout year.	Theoretical model focused on vector orientation.	Orientation of movement as a result of temperature (seasonal). Distinguishes between elastic and inelastic deformations.
Fiorucci et al. (2018)	Italy, Acuto	Limestone (Mesozoic)	Abandoned quarry, slope facing S and E	For 2 years: RT sensors and WST on top of quarry. IRT system used on monthly basis (day light).	ΔRT is higher in winter than summer, although RT ranges 30°C to 43°C in summer. Highest variation in fall/spring with daily ΔT 20°C	Theoretical T-2D model of heat flow across joints	(1) IRT helps evaluate cooling rates, discontinuity effects and heat flow within rock masses when integrating to TM research. (2) Sun light irradiates differently according to strike of slope
Collins et al. (2018)	United States, California	Granite	Dome-shaped horizontal surface as part of dam	During 3 years with borehole extensometer, acoustic emission sensors, rock and air temperature sensor.	Fracture aperture ranging 15 mm, larger apertures in summer. Rock temperature from 20°C to 40°C.	Theoretical calculation of stress intensity.	Cycles between temperature and fracture opening are out of phase (delay in opening). Failure below strength limits in a rock mass.
Guerin et al. (2019)	United States, California	Granite	Rock bridges which hold slabs to a steep rock slope (500m)	For 3 hours on 8 th October 2018: IRT integrated with Digital RGB camera	RT contrasts in IRT images due to presence of rock bridges, angle of IRT to surface and rock emissivity	COMSOL, T-2D Theoretical, TM-1D	Air circulation cool down sides of slabs close to rock bridges, registered as thermal anomalies by IRT. Potential use to assess structural state of rock masses
Marmoni et al. (2020)	Italy, Acuto	Limestone (Mesozoic)	Abandoned quarry, slope facing S and E	During 34 months. Weather station, temperature sensors at depth, strain gauges and joint gauges.	Annual temperature cycles ranging from 0°C to 40°C. Strain series from -400 to 200 μstrain	FLAC®, TM-2D	Development of a 2D model in FLAC®, with joint parameters calibrated with real observations. Conceptualization of "thermal joints" to model rock masses.
Gasc-Barbier et al. (2021)	France, La Roque-Gageac	Limestone	Limestone cliff with a cave of 10m long and 14.5m rock hanging on top	During 5 years (2010 to 2014). Extensometers, crack meters, temperature sensor, weather station.	Annual range of temperature from 10°C to 30°C.	Theoretical calculation of stress variation to reach tensile strength.	Thermo-mechanical approach to quantify fracturing as a result of fatigue. However, authors consider instantaneous fracturing rather than cyclic fracturing.

2.4 Lessons Learnt from Literature Review

Dynamic fatigue crack growth under transient conditions poses challenges in geotechnical research compared to static fatigue. While Paris' law provides a framework for understanding crack propagation, it overlooks the crack initiation phase and tends to underestimate the extension of short cracks, particularly in brittle materials. Moreover, the advent of thermo-mechanical fatigue introduces new complexities, with crack growth rates being higher in thermo-mechanical fatigue induced by temperature cycles compared to isothermal mechanical fatigue. Understanding the interplay between thermal fluctuations and mechanical loading is crucial for assessing material lifespan accurately, necessitating the development of robust analytical models capable of encompassing the intricacies of TM fatigue-induced damage.

The Goodman diagram is essential for analysing thermo-mechanical fatigue by graphically representing maximum and minimum permissible cyclic stress levels, so it aids in predicting fatigue limits. It helps identify safe range of exposure for rocks under fluctuating thermal and mechanical stresses. Its versatility accommodates various loading scenarios, including low-frequency and low-amplitude dynamics typical in thermo-mechanical fatigue in rocks. Thus, the Goodman diagram remains vital for characterising damage in rocks. As research in this field progresses, there is a need for comprehensive models that can account for the complex interactions between stress, temperature, and rock mass properties, ultimately enhancing our ability to predict and mitigate fatigue-related failures in engineering and geological applications.

Extensive research has been conducted on subcritical cracking processes and thermo-mechanical fatigue in rock engineering, exploring terms such as stress corrosion, micro-cracking, and static fatigue. Studies since the 1980s have emphasized the kinetic nature of subcritical cracking, with recent investigations focusing on scaling thermo-mechanical concepts to rock masses. Global monitoring efforts have increased, utilizing integrated systems to understand the relationship between temperature fluctuations and rock deformation, though further research is needed to integrate and elucidate observed relationships. The conclusive statements derived from Table 2-1 are as follows:

1. Thermal fatigue can occur across a wide range of lithologies, morphologies, and temperature ranges worldwide, without requiring sustained warming of the rock mass over an extended period. However, there is typically a considerable temperature differential ($\Delta 20^{\circ}\text{C}$) observed between seasons. In some studied locations, the rock surface temperature fluctuates daily by approximately $\Delta 10^{\circ}\text{C}$, leading to significant alternating stress magnitudes acting on the rock mass.

2. Displacements are generally small, typically less than $\Delta 1\text{mm}$, with a few exceptions where accelerated motions are observed. Trends in small displacement ($<\Delta 1\text{mm}$) are observed to be reversible, oscillating around a certain midrange stress magnitude that increases with time, resulting in sustained motion.
3. Temperatures result from a combination of local weather conditions and rock mass properties, emphasizing the importance of measurement by a weather station (including air temperature, air pressure, relative humidity, wind speed, wind direction, solar radiation, and cloudiness) and rock temperature with depth, using contact or passive infrared thermographic sensors.
4. Longer acquisition times lead to a better understanding of thermal fatigue, as the response of the rock mass is observed in different scenarios temporally linked to each other. This facilitates the capture of past specific conditions and prediction of the future state of the rock mass under potential future climate scenarios.
5. Numerical models, both analytical and simulated, have primarily been explored in 2D. While this may suffice mechanistically, it fails to account for all thermal gradients originating between all edges towards the interior part of the rock mass, thus lacking a true representation of the thermal state of the rock mass.

Finite difference methods (FDM) are commonly used in thermo-mechanical simulations of rock masses, particularly in software such as UDEC and FLAC from Itasca. A key advantage of FDM lies in its time-domain formulation, as opposed to the stress-based approach of finite element methods (FEM). This time-domain emphasis allows FDM to model dynamic and time-dependent processes, such as thermal and mechanical interactions in rock masses, with high fidelity (Itasca Consulting Group, 2019). Mathematically, spatial and temporal domains of the rock mass state and the perturbations are discretized into a system of linear equations, enabling the handling of multiple loading sources. However, FDM can be more computationally intensive than FEM when dealing with complex geometries.

The self-programming characteristics of Itasca's software further enhance FDM's utility, allowing users to customize models to incorporate a range of temperatures, perform sensitivity analyses, and calibrate against real-world observations. Many studies have utilized such software to investigate thermal expansion, stress concentration, and the effects of temperature on the mechanical properties of rock masses, including the development of fractures over time (see Table 2-1). Additionally, at the grain scale, researchers have employed FDM to explore crack propagation and the coalescence of micro-cracks. The flexibility of FDM is particularly valuable for

simulating diverse geological and climatic conditions, where thermo-mechanical fatigue plays a significant role.

For instance, Vlcko et al. (2014) already observed the effect of temperature oscillations to stress tensor changes associated with reversible displacements. Marmoni et al. (2020), also studied the thermal continuity of joints, and a measurement of heat conduction helped in determining the contrasts in thermal conductivity between intact rock and joints for modelling purposes.

The definition of thermal boundaries is pivotal in the thermo-mechanical analysis of rock masses; this will integrate the thermal fluxes and define the stress tensor fluctuations with time. Hence, coupling the thermal and mechanical components through time is a common procedure from the authors' approach that it is followed in this research. The analysis of heterogeneity of rock masses in terms of specific features and properties for calibration purposes is also studied in this research, however it is not clearly differentiated by previous research in this topic. The thermo-mechanical fatigue prediction is established with stresses and crack growth according to static or dynamic loading types, however the transient stress distribution is overlooked in the fracturing definition. FDM enables the prediction of where and when rock masses may fail due to repeated thermal and mechanical loading.

Overall, the use of FDM in numerical modelling helps in adding the rock mass condition and exposure, resulting in the fundamental inputs to characterize thermo-mechanical fatigue, such as the stress tensor dependency with time. Previous authors have correlated the fluctuations of temperatures with the displacements, observing the data trends to explain the interplay from a qualitative perspective. This research aims to conceptually link the perturbations to the rock mass response through the use of Goodman's diagram (1899) for fatigue, with the data provided from the numerical models. A series of steps are defined to explore the measured and simulated data, and to refine inputs in the iterative process of modelling. Such an approach is methodologically followed in this research for both Långören Island and the Valley of the Kings sites, and it is proposed that this approach can even be applied at other locations at which rock mass subcritical conditions and thermo-mechanical fatigue potential are observed.

CHAPTER 3 METHODOLOGY

The overarching methodology aims to establish a connection between the state of the rock mass, characterized by factors such as geometry, stress regime, and discontinuities, and transient environmental conditions like air temperature, relative humidity, sun radiation, and wind speed. This linkage was essential for understanding the dynamics of fracture growth in jointed rock masses under thermo-mechanical fatigue in near-surface environments. The analysis delved into heat fluxes, thermal-induced stresses, and strains within the rock mass, driven by thermo-mechanical forces, thus advancing the theoretical framework for thermally assisted fatigue failure at the rock mass scale.

3.1 Site Investigation

The research focused on the rock mass scale fracturing events, so it was essential to identify locations at which fracturing or displacements of new and existing fractures occur. Hence, an identification of morphologies and critical state of the rock masses was studied through the literature, as listing in Table 2-1. Despite thermo-mechanical fatigue is studied in several geological and climatic conditions, this investigation explored two study sites before the formal conceptualization for the thermally assisted fracturing.

The two sites were the Långören Island (Finland) and the Valley of the Kings (Egypt). Information collected at both locations included geological mapping and environmental context characterization. Quantitatively, the data were acquired to comprehensively understand the geological, geotechnical and climatic context and their relationships. Relevant structures and morphological features that may cause fracturing or fluctuation of displacements were identified. This allowed the characterization of the movement nature and the key triggering agents. To capture the short and long term behaviour of the rock mass, a monitoring system was installed to track the exposition and response of the rock mass. For Långören Island, the research context and site monitoring was published in Alcaïno-Olivares et al. (2018), whereas for the Valley of the Kings the site characterization was documented in Alcaïno-Olivares et al. (2019).

The monitoring system at both sites are capable to report the environmental context and resulting rock surface temperature acting on the outer surfaces as a result of the natural climatic fluctuations. In addition, the thermo-mechanical response of the rock mass was recorded from the sites with a real-time reporting system that allowed to collect data remotely to minimize the interference of human activities at the sites. Installation and system performance were documented, aiming to maintain and enhance the ground investigation.

3.2 Laboratory Testing

Samples from the study sites were collected to undertake laboratory tests. For the Långören Island case, samples were collected from one hand and one cored samples. Sub-coring of samples delivered 11 specimens that were characterized in terms of their tensile strength and compressive wave velocity measured at different orientations. Numerical contrast in wave velocity measured at different orientations suggested the existence of micro-fracturing related to the long fracture extension in the horizontal direction, as discussed in Alcaïno-Olivares et al. (2018, 2021).

Conversely, the Valley of the Kings case included an extensive rock mechanical laboratory test with samples of four rock units collected from the valley. The documentation of this test program tests was the most comprehensive set of geotechnical parameters for the Theban Mountains, and it was reported in Alcaïno-Olivares et al. (2022) including the test of 97 specimens. The King's Valley tests included characterization of petrophysical (bulk density, apparent porosity, slake durability index, wave velocity, thermal conductivity, volumetric specific heat), strength (Brazilian tensile strength, uniaxial compressive strength), and strain measurements during uniaxial compressive tests (Young's modulus, Poisson's ratio, crack closure and crack initiation). The procedures and standards to measure these properties are cited in CHAPTER 4 and CHAPTER 5, while a summary of the tests is listed as follows:

1. Bulk density: Measured in accordance with ISRM (1977) using calipers to determine bulk density. This test was conducted only for Egyptian samples, excluding argillaceous limestone.
2. Apparent porosity: Performed following ASTM (2010) to measure interconnected void volume. This test was limited to Egyptian micritic limestone samples, as other rock types exhibited a swelling potential when in contact with water.
3. Slake durability index: Conducted following the Franklin and Chandra (1972) procedure. Tests were limited to Egyptian micritic and marly limestone samples.
4. Wave velocity: Measured in accordance with ISRM (1978) using transducers to determine wave velocity in rocks. This test was performed on samples from both Finland and Egypt.
5. Thermal conductivity and volumetric specific heat: Measured using a thermal analyzer (KD2 Pro), following the manufacturer's guidelines (Decagon Devices Inc., 2015). These tests were conducted exclusively on Egyptian samples.
6. Brazilian tensile strength: Conducted in accordance with ISRM (1978) recommendations for the Brazilian tensile strength method. Samples from both Finland and Egypt were

tested, except for argillaceous limestone, which could not be tested after coring due to reactions with water.

7. Uniaxial compressive strength and strain measurements: Performed in accordance with ISRM (1979), with strain gauges attached. These tests were conducted only on Egyptian samples of micritic and marly limestone. Stress thresholds, such as crack closure and crack initiation, were determined using several methods (Brace et al., 1986; Lajtai, 1974; Stacey, 1986; Diederichs, 2007; Ghazvinian, 2010), and elastic properties were calculated within the corresponding elastic region.

It is important to highlight that the present investigation did not focus on conducting laboratory tests to understand the dependency of the rock properties to damage and temperature. This research relates to the rock surface temperature range below 100°C, as other researchers have studied, at which rock properties do not vary significantly with temperature.

3.3 Time-series Analysis

The data gathered from the rock mass response supported the proof of concept for the existence of active thermo-mechanical responses, or indicated to improve the monitoring system through more instrumentation. Through a combination of data processing to link between mechanical and thermal cycles, the Libelium Agriculture Pro data acquisition (Libelium, 2022) and monitoring systems was selected since it could capture the thermal perturbations, the rock mass state and the thermo-mechanical response of specific features that were affected by thermal cycles. The analyses were reported in Alcaïno-Olivares et al. (2021) for Långören Island, and in Alcaïno-Olivares et al. (2020) for the Valley of the Kings. The monitoring system is detailed in chapter CHAPTER 5.

Upon confirming the quality of the monitoring system, the datasets were examined to delineate the actual heat sources within the rock mass in terms of amplitude, frequency and spatial distribution. The analysis involved two main stages: comparing measured weather parameters from the on-site monitoring station with reports from nearby weather stations and comparing model predictions against measured data to evaluate the model's performance and accuracy.

Weather parameters, including temperature, humidity, and solar radiation, were collected from the monitoring stations. For Långören Island, the data were compared to data collected by stations at other islands and inland, reported by the Finnish Meteorological Institute. Whereas in Egypt, the data were compared using a station within the valley above tomb KV62 and another at Luxor Airport. The comparisons were performed using the Pearson Correlation Coefficient (R^2) to

evaluate the degree of linear correlation between datasets, with values closer to 1 indicating stronger correlations. Additionally, relative differences between the two datasets were calculated as the measured value subtracted by reference value. This provided a quantitative measure of agreement between the two data sources, complementing visual comparisons of trends. The analysis that the on-site weather data was representative of regional conditions while accounting for localized variations.

The thermal and thermo-mechanical models were compared against measured temperature distributions within the rock mass to validate their accuracy, as well as the measured crack openings. This involved calculating the coefficient of determination (R^2) to quantify how well the model predictions explained the variability in the observed data. The R^2 values were derived from regression analyses of model outputs against the magnitude and distribution of discrepancies between predicted and observed values. Relative differences were also calculated to quantify the average deviation and highlight significant outliers in the model's predictions.

The relative differences between model predictions and measured values were also visually compared by plotting temperature profiles and identifying key deviations. This method allowed for a conceptual understanding of where and why discrepancies occurred, particularly in regions with complex geometries or discontinuities such as joints.

The integration of thermal boundary conditions involved measuring and conceptually analyzing the spatial and temporal temperature distribution within the rock mass. Special attention was given to regions affected by joints and other discontinuities, where deformation under thermal stresses was more pronounced. The dynamic behaviour of these boundaries was used to refine the model, ensuring that it accurately captured the impact of complex geometries on temperature distribution and associated deformations.

The thermo-mechanical cycles were primarily described with the correlation between displacements of monitored fractures, so-called fracture opening data, and the rock surface temperature. This correlation was integrated in a rock temperature versus fracture opening diagram, showing the interplay of the thermo-mechanical cycles and delivering a ratio of deformation in mm/°C, and a rate of deformation in mm/year. Note that only a few number of authors have published these indices so far, so there is no clear scaling of these parameters with future rates and thermo-mechanical behaviour yet (Merrien-Soukatchof and Gasc-Barbier 2023, references therein).

A more robust integrated analysis of multiple sensors and longer data sets may highlight the dominant variables leading to thermo-mechanical cycles, which is currently limited to rock surface temperatures for the purpose of this research and the environmental influence on this resulting temperature.

3.4 Numerical Modelling

Numerical models were developed using finite difference methods (FDM) with Itasca FLAC® and FLAC3D® software for this research. While other methods could potentially be applied for thermo-mechanical displacement simulations, FDM was chosen for its capacity to solve time-dependent problems efficiently, which is crucial for transient simulations. A key advantage of Itasca's applications lies in their integration of the programming language FISH, enabling greater flexibility to incorporate custom functions and parameters tailored to the unique conditions of each study site. Applications using finite element methods (FEM) were not considered for transient thermo-mechanical simulations, as FEM relies on matrix solutions for large arrays, which can significantly increase computational memory requirements and solution time. Despite these distinctions, numerical models can be constructed using either FDM or FEM depending on the specific requirements of the study.

FDM was selected due to its time-domain approach, which makes it particularly suitable for problems requiring the sequential computation of dynamic, transient responses over time. The method discretizes the spatial and temporal domains into smaller units, solving equations iteratively for each time step. This approach aligns well with the focus of this research, which involved simulating the progression of thermal cycles, temperature gradients, and associated rock displacements. FDM's ability to incorporate non-linear behaviour and complex boundary conditions also allowed for more detailed simulations of phenomena like fracture propagation and stress redistribution under varying temperatures. Furthermore, the flexibility to model thermo-mechanical coupling provided an essential framework for calibrating and validating the models against real-world data. These characteristics made FDM the most appropriate choice for this study.

The numerical models were designed to replicate the thermo-mechanical response of the rock masses during the observed periods, with the inputs derived from site investigations, data acquisition, and laboratory tests. Constructing the models involved defining the boundaries, geometries, and discretization of the study areas. The refinement of model inputs was critical to achieving calibration. Inputs included thermal properties, elastic parameters, strength properties, and measured environmental conditions, which were iteratively adjusted to match the measured

displacements. The model's performance was evaluated through Pearson Correlation Coefficient analysis, relative differences, and comparisons of time-series data for key parameters, including peaks and troughs. In addition, visual inspections were also carried out at points of interests. These methods ensured the models provided a reliable representation of the site-specific behaviours.

For Långören Island, a two-dimensional exploratory model in FLAC simulated the crack aperture of horizontal fractures associated with thermal cycles. The dataset was divided into two subsets representing portions of the observed period, allowing calibration against measured data in stages. The modelling process involved an initial thermal calibration to match observed temperature profiles at depth, followed by calibration for displacements. In contrast, the Valley of the Kings models included both two-dimensional and three-dimensional approaches. The two-dimensional models were constructed along East-West and North-South cross sections to examine fracture opening and the interaction of structural features. Calibration for these models began with thermal adjustments before incorporating thermo-mechanical properties. Model performance was assessed through visual inspection, Pearson Correlation Coefficient values, relative differences, and time-series comparisons for data spanning April 2018 to June 2021, with results for the two-dimensional model published in Alcaïno-Olivares et al. (2023).

The three-dimensional model for the Valley of the Kings involved three stages: mesh creation, mechanical analysis of parameters, and thermal calibration. A Digital Elevation Model (DEM) of the area was simplified to remove irrelevant features while preserving critical geometries. The mesh was optimized using shape, size, and distortion criteria, along with mechanical simulations for basic elastic parameters. Mechanical inputs were evaluated using the Hoek-Brown constitutive model, incorporating joint systems. Thermal analyses tested surface properties and calibrated the rock's thermal response.

The coupling of mechanical and thermal simulations allowed for the calculation of displacements, which were compared to measured data. An initial calibration phase spanning 12 months involved broad parameter variations to refine the model. Subsequent adjustments correlated simulated data with the complete dataset from April 2018 to July 2023. Various strategies were tested to replicate stress distributions and the observed annual increases in peak displacement values associated with fatigue-driven fracture extension. The most optimal simulation reported deformation ratios and rates, alongside calculated stress tensors that varied with temperature, demonstrating the robustness of the FDM approach in solving time-dependent thermo-mechanical problems.

In summary, FDM was chosen due to its strengths in handling time-domain simulations, accommodating complex boundary conditions, and offering flexibility in model customization. These advantages made it the ideal choice for studying the transient thermo-mechanical behaviour of the rock masses at both study sites.

3.5 Analytical Modelling

A conceptualization of thermo-mechanical fracture growth involved the use of Goodman's diagram (see Section 1.2.3) to schematically represent the current state of the rock mass and predict failure, through the use of midrange and alternating values from the Valley of the Kings modelling's result. A proposed failure criterion caps the stress fluctuations on each cycle in terms of the resulting deviatoric stress subjected to temperature cycles. The fluctuation limited by the ratio of deviatoric stress to crack initiation (CI) in the vertical and horizontal axes, following Goodman (1899) or Gerber (1874) criteria which both define a fatigue region.

The analytical model highlighted the features varied wider in terms of stress distribution, which were later plotted individually in a series of temporal plots associated with specific cycles of temperatures. The plots showed the movement along midrange and alternating deviatoric stress ratio to CI, constructing the story for the short evolution of the site in the period between 2018 – 2019. The main assumption is that the rock mass will only fluctuate thermally, so no accelerations from earthquakes or changes in the surrounding area is exhibited, unless cracks extend up to the point that the mechanical stress tensor is modified, hence the deviatoric stress changes. Also, it is also assumed that CI or UCS properties do not vary with time, establishing the fatigue limit as fixed over the entire simulation. Hence, the system will reach thermo-mechanical fatigue when either of the relevant features moves beyond the fatigue region, redistributing stresses in the whole rock mass that can mobilize other features to a subcritical state, so thermo-mechanical fatigue can become relevant for the stability of those areas.

Theoretically, based on mechanical and induced stresses, two regions are conceptually delineated as mechanical and thermal regions for stress evolution. A competition between mechanical and thermal region is formulated over time to a new state. This new state inherently would shorten the range of induced stress from thermal fluctuation. This is shown in Figure 3-1a. Over time, or cycles, the new balance reduces the peak and troughs temperature that a rock can withstand, and also its ranges of fluctuation. Therefore, regardless of previous cycles, the ultimate failure of rock due to thermo-mechanical fatigue is reached when no fatigue cycle is allowed anymore, as progressively shown in Figure 3-1b. For the midrange and alternating deviatoric

stress ratio versus time (or cycle) the conceptual evolution depicts the accumulated damage along several cycles of repeated thermal load.

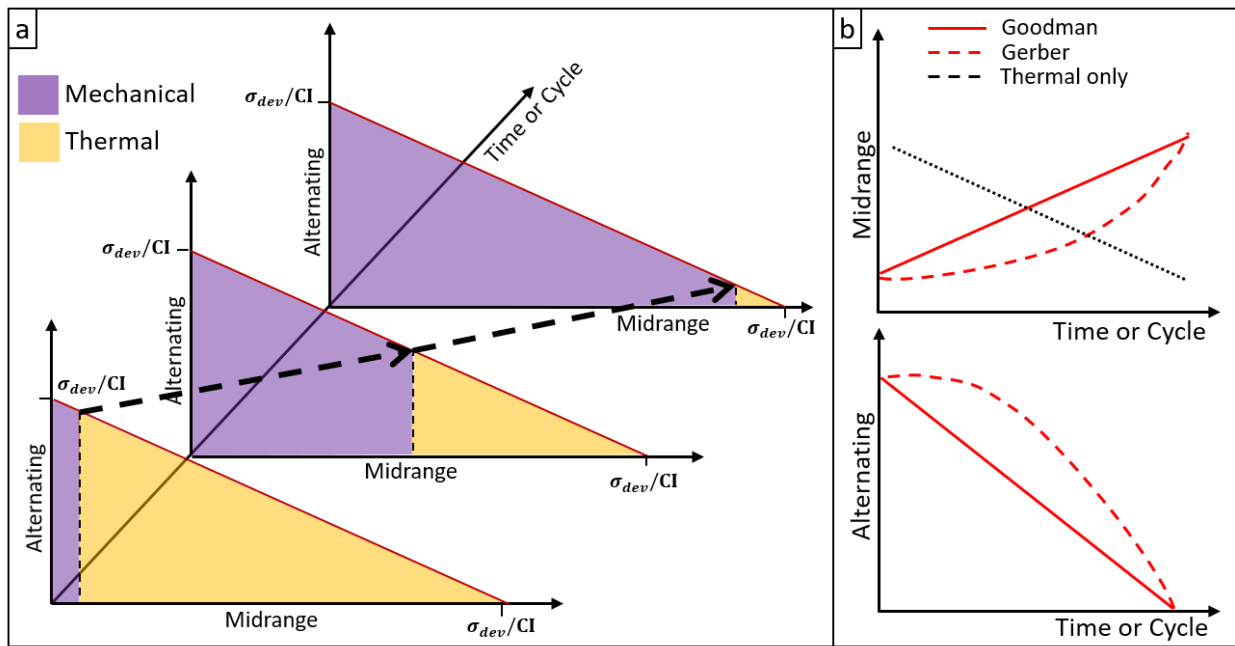


Figure 3-1: Conceptualization of analytical modelling for thermo-mechanical fracture growth due to repeated load cycles acting on rocks, showing a) a diagram of three axis with the stress distribution at different stages and the mechanical influence of material to represent the long-term behaviour of the rock mass; and b) a schematic evolution of midrange and alternating deviatoric stress ratio (σ_{dev}/CI) along time (or cycle).

3.6 Sequencing of Methodology

In accordance with the objectives of this research, the investigation phases have been meticulously structured to validate the monitoring system and assess data quality before proceeding to numerical modelling. As depicted in Figure 3-2, and drawing from collective insights gleaned from research endeavors worldwide, an initial contextualization of lithologies, geometries and climatic variables at the study sites was documented. Notably, the characterization of thermal loads yielded valuable insights into the exposure of the monitoring system and its operational functionality, encompassing aspects such as installation procedures and inherent limitations.

To this end, climatic cycles and rock properties of the site were extensively reviewed to characterize the mechanical and thermal loads acting in the rock mass. The geometry and stability condition is essential to determine the features prone to thermo-mechanical fatigue, such as fracture extension or joint aperture at slopes or bedrocks. The thermo-mechanical fatigue is examined through the data collection from a monitoring system, which is enhanced in accordance with the quality of the measurements.

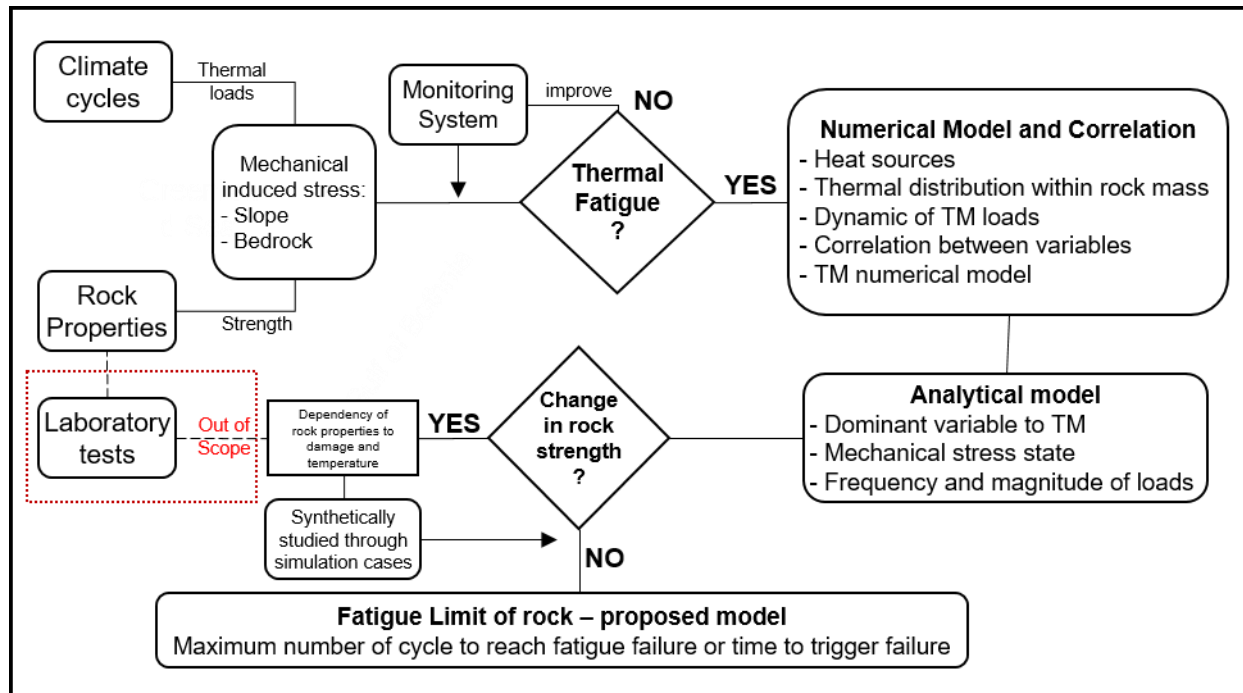


Figure 3-2: Flow diagram to summarize the methodology of this doctoral research.

Further analysis of the measured time-series for displacements and temperature distribution within the rock mass as pivotal to prove the thermo-mechanical action. Examination of the heat sources and the dynamic of the thermo-mechanical loads helped in constructing a numerical model to simulate the study cases. This process involved the selection of key inputs and the relationship between thermal boundaries and rock surface temperature. Given the model's capability to simulate thermo-mechanical measured data, the results helped in the definition of parameters variable to thermo-mechanical cycles. Furthermore, simulations deliver the mechanical and induced transient stress and strain tensors, highlighting frequency and magnitude of these results.

Due to the potential for crack growth, and extension of existing fractures, inelastic displacements and failure due to fatigue are expected. Assuming that failure does not relate to change in rock mass strength, a fatigue limit for rock mass is proposed with the number of cycles needed to reach visible failure. Otherwise, failure as a function of rock strength deterioration from temperature fluctuations is out of the scope of this research and this dependency is only studied through sensitivity analysis in few modelling instances. The fatigue limit is proposed for the long-term analysis only, such as yearly trends. The short-term fluctuations, for instance during fracturing within daily or monthly fluctuations, are not incorporated in this analytical model.

3.7 Case studies context

Thermo-mechanical fatigue is not a particular phenomenon for a set of geological and climatic conditions, rather it can be observed in several contexts. The main differences across locations are on the morphology and monitoring systems. To this research's goal, two sites are studied following the methodology set out previously. Both instances, of large differences between each other, were part of different investigations that converged together as rock masses under subcritical conditions, potentially exposed to thermo-mechanical fatigue.

The first site is in Långören Island, situated in the Finnish Archipelago on the Baltic Sea (Finland, northern Europe), which experienced spontaneous fracturing on a horizontal dome-shaped surface during an uncharacteristically warm summer in 2014. The rock unit is micro-cline granite, with discontinuities of quartz veins of 10 to 30 cm in width. Active fracturing was recorded by the owner of the island and reported to the Finnish Geological Survey, which led an investigation and field assessment in 2016. The present investigation emerged after the first findings, with subsequent fieldworks in 2018 and 2019. The site investigation concluded in March 2019.

The second site is in the Valley of the Kings, situated in the Shara Desert within the Theban Necropolis of Luxor (Egypt, northern Africa). The valley is surrounded by tall cliffs of 20 to 40 m in height, with hanging blocks formed by fracture extension, in a sequence of units of limestone from the Thebes Limestone Formation. The site was declared a UNESCO heritage since it holds tombs of pharaohs and their relatives who reigned in the New Kingdom Egyptian era (3500-3000 BP). Hence, the area holds international and archeological significance to investigation and tourism.

Specifically, above one of the tombs, called tomb KV42, a hanging block stands in a subcritical condition. This block, so-called rock column, is 20 m tall and hanging on its western side by a rock bridge that connects the rock column to the adjacent cliff. Historical reports such as photographs, reports and journals have pointed out this column since the first excavation of KV42, dating back to circa 1920. Nevertheless, the generation of slabs between the joints and the condition of the toe of the rock column motivated the installation of a monitoring system to track lateral displacements of the rock column, which was integrated with temperature sensors. This system recorded the thermo-mechanical behaviour of the rock mass. The system was installed in April 2018 coinciding with the inception of this research. Subsequent campaigns conducted in 2019, 2020 and 2022 helped in enhancing and maintaining the system.

Given the greater involvement in the Valley of the Kings site, this doctoral research predominantly focuses on this site. Therefore, the study is divided in a first approach to thermo-mechanical

fatigue analysis conducted with data from Långören Island, to transition to a more extended and comprehensive study of the Valley of the Kings. The methodology sets out in this chapter compiles the basic steps followed in both sites, yet the analytical model is explored only to the rock column above KV42. This does not only relate to the longer data acquisition time-frame but also to the opportunity to analyse the fatigue under dry conditions. The Valley of the Kings site is located in a desert climate with rare rain, and minimal influence of other processes that could contribute to fatigue such as biological activity, chemical reactions or mineral hydration. It provides a better understanding of the dynamic for cycling loads, to characterize the frequency and amplitude in both temporal and physical spaces. In addition, it also formulates specific driven agents at which thermal-mechanical fatigue may occur. Particularly, since this type of fracturing may not be an isolated phenomenon, hence a long-term data gathering must be captured for one main triggering parameter, prior to move onto new stages in such a research.

CHAPTER 4 A FIRST APPROACH FOR THERMO-MECHANICAL FIELD OBSERVATIONS – THE CASE OF LANGÖREN ISLAND

4.1 Preface

This chapter introduces the site investigation conducted in Långören Island between 2018 and 2019, including the data curation and numerical modelling to simulate the spontaneous fracturing that occurred in the island during the summer of 2014 and 2018. The hypothesis is that a thermo-mechanical processes triggered the active and spontaneous cracking, which related to unusual temperatures. The initial site investigation and the formal analysis served to test the research methodology at a smaller scale, whereas the main findings were documented in two conference papers at the Canadian Geotechnical Society, referenced as follows:

Alcaíno-Olivares, R., Hayden, D., Perras, M., Leith, K., and Low, S. (2018) Fracture Growth on Långören Island, Finland, on the Hottest Day on Record in 2014. GEO Edmonton, Alberta, Canada.

Alcaíno-Olivares, Leith, K., Ziegler, M., and Perras, M.A. (2021) Thermo-mechanical fatigue cracking of the bedrock on an island in the Baltic Sea. GEO Niagara 2021, Ontario, Canada.

The authors express their gratitude to the Geological Survey of Finland for their initial interest in this fracturing event and sharing data with the research team. Our deepest gratitude goes to Mr. Aleksei Sarpaneva and his family, the owners of Långören Island, for their scientific interest support during the fieldworks and permission to install the monitoring system. Funding was provided by the National Science and Engineering Research Council of Canada (NSERC) through the Discovery grant program (grant reference RGPIN-2018-05918).

4.2 Chapter Introduction

Långören Island ($59^{\circ}59'N$, $22^{\circ}7'E$) is in the south-west of Finland, within an archipelago of about 20,000 islands (Figure 4-1). This archipelago marks the border between the Baltic Sea and the Gulf of Bothnia, covering 8,000 km². In July 2014, during the hottest day in Finland, reaching 30°C, a dome-shaped portion of the rock mass on Långören Island suffered from a sudden and dynamic extension of horizontal cracks, with apertures of 5 mm to 20 mm. This event was also recorded again in July 2018, when temperatures rose again over 30°C, unusual for this area. In late 2015, an instrumentation plan was developed for the island to monitor the existing fracture behaviour and to identify new fractures. The system was installed in July 2016, later updated in August 2018, and finally dissembled in March 2019.

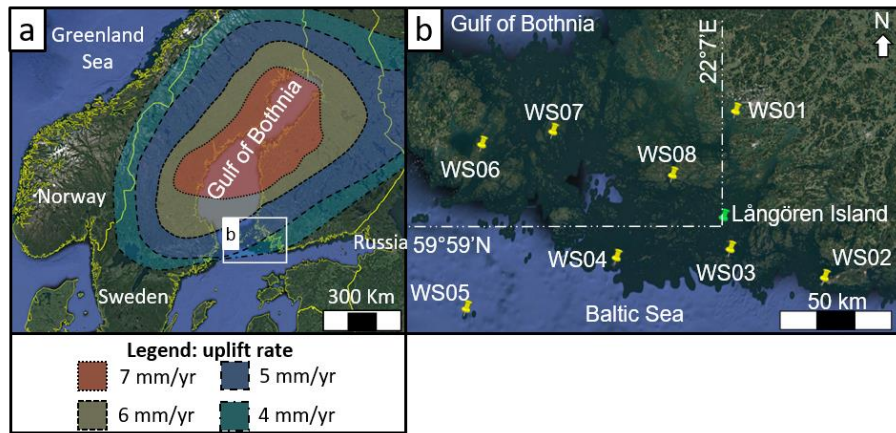


Figure 4-1: Location of Långören Island a) in the Scandinavian region and b) within the Finnish archipelago. The uplifting crustal rates associated with the glacier retreat are sketched for the whole region (Poutanen et al., 2010). Weather stations from the Finnish Meteorological Institute are labelled around the island, whose data are used later to confirm measurements from Långören Island. ID are detailed in Table 4-3. WS##: WS stands for weather station and ## indicates the station number adopted for this research purpose.

4.3 Site Investigation and Monitoring System

In July 2014, a dome-shaped portion of the rock mass on Långören Island suffered from a sudden and dynamic fracturing event (Figure 4-2a). Although the dome-shaped topography is capable of generating bending moments (i.e. high tensile stress concentrations), a preliminary assessment revealed that the topography itself could not lead to failure on its own, but it was presumed to have been assisted by the extreme temperatures recorded in the Finnish Archipelago (Rantanen 2016). The investigated cracks grew horizontally, exposing very thin slab edges, ranging between 5 mm and 20 mm in thickness (Figure 4-2b,c). However, based on borehole observations and inferred extension to surface locations there are two horizontal rock slabs in the order of up to 100 mm in thickness.

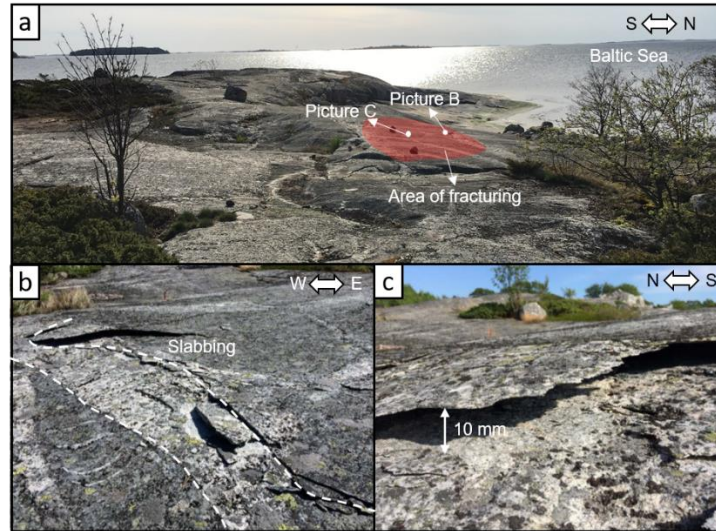


Figure 4-2: Pictures of Långören Island, showing a) an overview of the site where fractures extended during high temperatures in 2014 and 2018. The size and distribution of the new fractures extended over the dome-shaped surface, with b) surficial expression towards W (down the dome) and c) variable apertures with an average of 10 mm. Pictures b and c are courtesy of Mr. Sarpaneva.

By the end of 2015, photos and mapping of the fractured zones were used to design a monitoring system to capture the response of the rock mass. The system was finally installed in July 2016. The fractures had been theorized as a consequence of the high temperatures (i.e., 30°C, unusual for Långören Island), so the monitoring movement of the upper slab could be correlated to the weather parameters. Sketched in Figure 4-3a, the crack growth was found to have developed as two fractures (F1 and F2), which separated the rock surface into two slabs, one on top of the other. This was seen in a cored borehole sample at the location of AE3 (Figure 4-3b). F1 reached the surface during the cracking of 2014, whereas F2 had shown no surficial expression in investigations prior to 2018. The distribution of mapped fractures from 2014 to 2018 is shown in Figure 4-3a.

The movement of the slab and growth of the existing fractures was deemed to be the critical element of the monitoring system. To measure the movement of the slab by using a crack meter, a borehole passing across the near surface fractures was planned. The crack meter (CM) was designed to be anchored in the rock below the fracture thereby allowing the vertical motion of the monitored slab. To ensure optimum anchoring of the borehole wall, coring was considered with the adding benefit that samples for laboratory tests could be obtained.

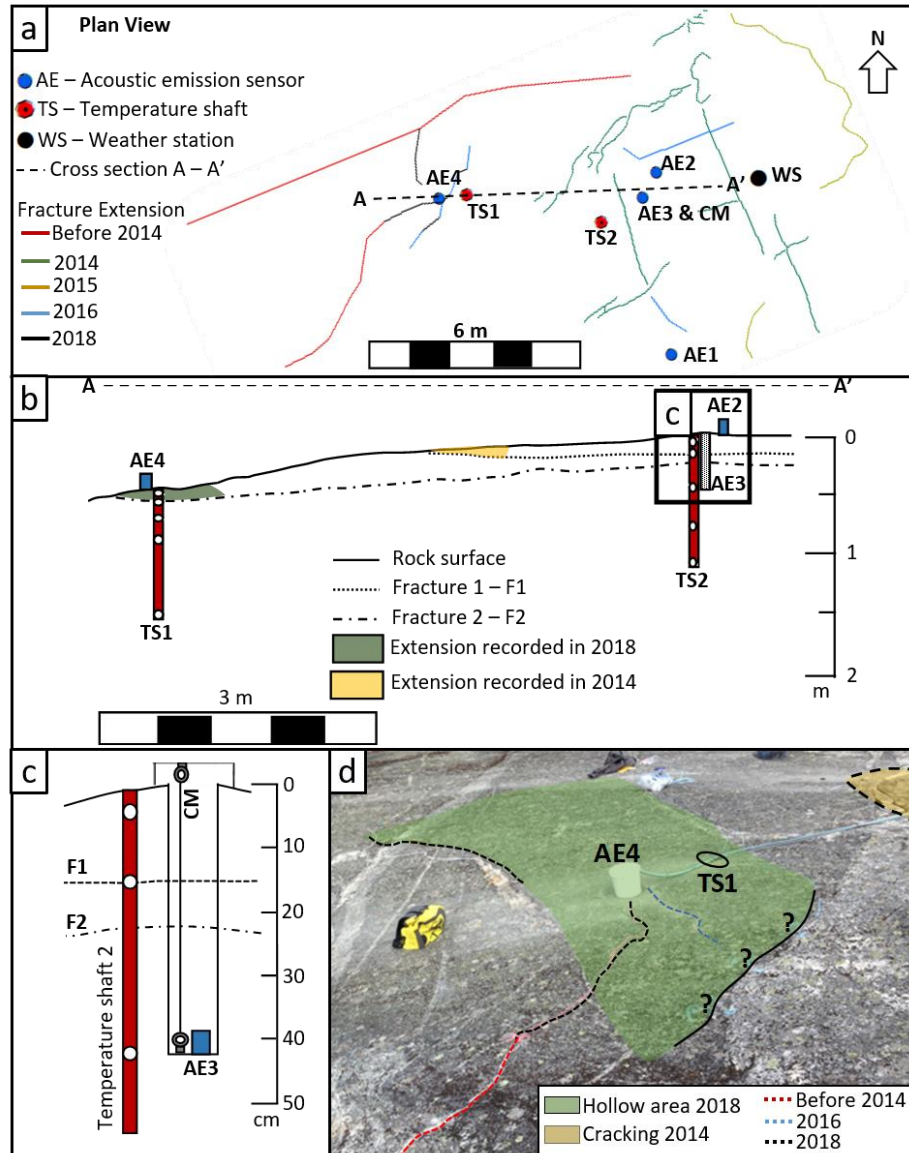


Figure 4-3: Monitoring system and geological inspection in the area of interest, with a) plan view of the area, indicating the position of sensors and mapped fractures, b) a cross section of the long fractures (F1 and F2) and crack growth observed in 2014 and 2018, c) an inset cross section showing the crack-meter (CM) position relative to the positions of F1 and F2, and d) a picture from 2018, including the latest cracking observations.

Since a crack meter only monitors one location, it was also decided to deploy a series of acoustic emission sensors (AE) to track the new fracturing of the rock and breaking asperities during movement of existing fractures. The AE system consisted of four sensors with a resonance frequency of 60kHz and built in 26dB preamplifiers. These sensors are contained in housing that intends to minimize the effects of both radio frequency and electromagnetic interferences. Plastic containers were placed over the sensors and filled with sand to eliminate noise from the exterior sources, such as wind or direct rain impact. The sensors were glued and anchored directly to the

exposed bedrock. The surface was ground flat before gluing to eliminate air pockets between the sensor and rock. The location of the sensors is shown in Figure 4-3. Three sensors were placed in surface, whereas one AW sensor was placed to monitor activity below the surface. The system was connected to a field computer running AW data acquisition system. The system was installed in trigger model to capture the waveform whenever an event was detected. The AE system was removed in September 2018 to conserve battery life and continue data logging of the other systems.

To track the temperature fluctuations within the rock mass, two temperature shafts (TS1 and TS2) were planned: one that was drilled off the slab such that it did not intersect the upper slab (TS1) and one that crossed through the lower slab (TS2). This was designed to understand the influence of the fracture on the rock temperature gradient. A destructive hammer drill was used rather than a coring machine due to the depth requirements and rate of penetration. These shafts were filled with coarse aggregate grout to have similar thermal properties of the rock. The temperature gradient strings were custom made using PT 1000 temperature sensors and an Arduino microcontroller for data acquisition. The data was accumulated on the field computer. The TS's recorded rock temperature with digital and analogue sensors. Digital sensors were placed at depths of 4 mm, 440 mm and 1000mm. A plan view with the monitoring system is presented in Figure 4-3b,c, along with the fractures indicated on the year they were observed. The boreholes were filled with coarse aggregate grout to have similar thermal properties to the rock. The temperature sensors were read once every 200 seconds.

A weather station (WS) was planned to make correlations between the thermo-mechanical measurements and the climatic variables. These were monitored with a Libelium Plug and Sense Agricultural Pro station, which included a dendrometer (for tree growth), which can be used as a crack meter when properly tested. The station was situated on a mast and the crack meter was associated with the cored borehole. The crack meter was placed at the ground surface and an anchor placed at the bottom of the borehole below two near surface fractures (see Figure 4-3c). The system logged the data locally, separate from the AE and temperature string system.

Filming and photographs of new cracking on the island were reported by the end of July 2018, which led to a new field campaign in September 2018. This focused on maintaining the monitoring network (i.e. power and reset remote connection to data loggers), as well as logging of new cracks and geological features. The CM was re-anchored so that it could measure the aperture given by Fracture 2 with time (Figure 4-3c). Mapping of new cracks were conducted at the west end of the area of interest, mostly linked the growth of F2 extending downhill, as shown in Figure 4-3. F2

reached the surface with cracks extending towards AE4, and the lower slab seemed to have been detached from the rock mass. This was tested with a hammer, enclosing an area for which a “hollow” sound was emitted when the surface was hit (Figure 4-3d). Another sign was the interruption of data acquisition in TS1, which had been originally installed to avoid intersection of F2. The observed new cracks in 2018 may have developed over a short or longer time, however, it is constrained by the observations from 2016. A last field campaign took place in March 2019 to map if any new cracks had developed, and as no additional cracks were exposed at the surface it was determined to uninstall the monitoring system due to difficulties in maintaining the station.

4.4 Literature Background of the Area

4.4.1 Geological Setting

The Finnish archipelago marks the border between the Baltic Sea and the Gulf of Bothnia, covering 8,000 km² (Figure 4-1a). The region was covered by a maximum glacier thickness of 2,500 m during the Holocene, extending over part of Norway, Sweden and Finland (i.e. Fennoscandian ice sheet). The glacier melting resulted in ground surface rebound with uplifting of the shallow crust at rates between 4 mm/yr and 8 mm/yr, as sketched in Figure 4-1a. (Edelman 1960, Johansson et al. 2002, Poutanen et al. 2010).

The studied island spans an area over 500 m by 200 m, surrounded by the Baltic Sea, 45 km from the Finish mainland. The geological domain of Långören Island is defined by Edelman (1960) as a microcline granite formed through granitization processes during metamorphism in the last stage of the orogenic evolution. The modes of granitization vary by composition and structure of the primary rocks (Edelman, 1960), forming domes possibly due to the plastic behaviour of the primary rocks (Virtasalo, 2006; Paulamaki et al., 2002; Edelman & Jaanus-Järkkälä, 1983). The geological evolution resulted in migmatites, magmatic granites, pegmatites, crystalline schist, and alkali-calcic igneous rocks, along with amphibolite dikes developed in a series of folds in the region.

The geological units were significantly eroded during the Cambrian era close to the current elevation (Edelman, 1960; Edelman & Jaanus-Järkkälä, 1983). A series of melting stages of the Fennoscandian icesheet since 14.000 BP have influenced the quaternary deposits, washing the sediments to the sea bottom. As the sea level rose the Paleo-Baltic Ice Lake was connected with the North Sea. This allowed saltwater infiltration and shaped the current sea conditions (Virtasalo, 2006; Granö et al., 1999). The glacial processes polished the rock surface, washed the weathered products, and exposed the current bedrock surface along with the structural features (Virtasalo, 2006).

The topography of the island is quite alike to other islands in the area, with a low-relief bedrock surface which reaches an elevation of 12 m.a.s.l. at the center of the island generally. In combination with the past glacier motion, Långören Island exhibits well-polished dome-shaped surfaces with glacier striation. Except for few locations where bedrock slabs have been removed and no marks of striations are visible, the signs of ice flow support the theoretical regional NNW – SSE glacier regression orientation. Major metamorphic features such as quartz veins and vertical fractures are often weathered (i.e. post-glacial weathering), with the less stable granite minerals being eroded (i.e. biotite, hornblende). The vertical fractures have short apertures (< 3 mm), forming polyhedral blocks. There are no streams or ponds on the island, and rainfall either evaporates, discharges to the sea directly or infiltrates in the shallow surface over short distances.

4.4.2 Hydrogeological and Climatic Setting

In the larger regional area, the sea can be divided into several channels which connect the central and northern part of the Baltic Sea. These are fed by fluvial discharge from the mainland contributing to sediment accumulation on the seabed (Kaskela, 2017). Locally, the western part of Långören Island is an exposed bedrock dome that transitions to a vegetated spit in the northeastern region. Surface runoff flows over the bedrock surface or infiltrates the thin, rocky soil cover. There are no streams or ponds on the island. The only trace of standing surface water includes shallow pools that are present after heavy rainfall and evaporate over time as the water cannot infiltrate the rock mass.

The climate displays large seasonal variations, having a wide range of extreme temperatures during winter and summer (Figure 4-4). Temperatures higher than the historic summer mean value of 18°C have been recorded in July and August over the last 4 years between 25°C to 30°C. The maximum temperatures ever recorded to date were in the summer of 2014. An observation from the precipitation indicates that there was less cumulative yearly rain in July 2014 than subsequent summers (Figure 4-4). Långören Island is in the region that receives the highest rates of radiation in Finland (Rantanen, 2016). Climate change during the last century has raised the sea level, air temperature, the amount of precipitation, and the wind speed. Jokinen (2010) points out that the combined changes in the climate may have caused a decrease in the salinity of the sea, likely contributing to potential changes in the rock mass in the near surface.

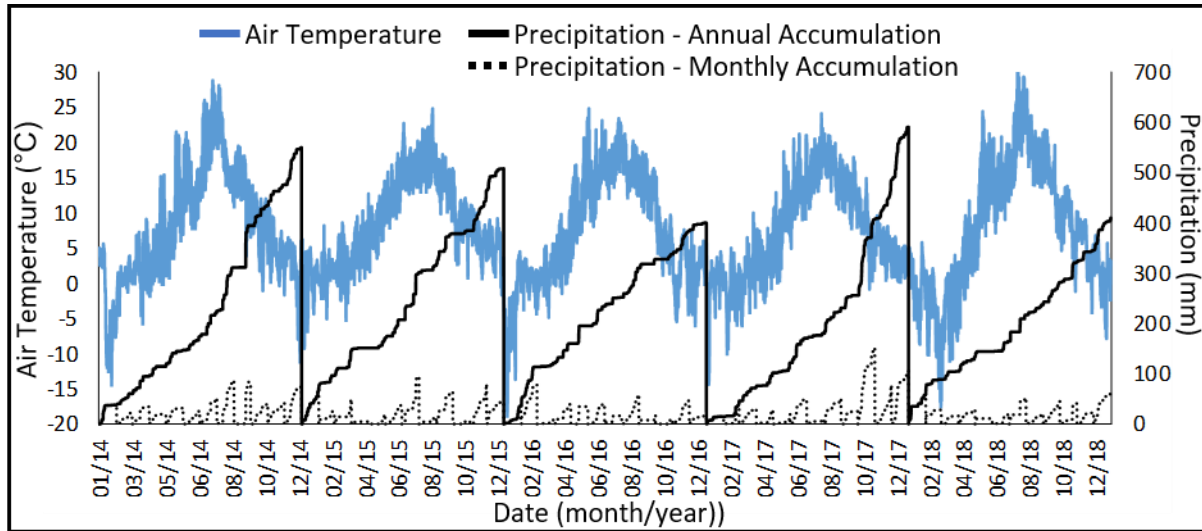


Figure 4-4: Regional values for temperature and precipitation at Långören Island, taken from the Finnish Meteorological Institute for Paranein Fagerholm weather station. Values are plotted from January 2014 to December 2018.

4.4.3 Geotechnical Setting

The assumed major principal horizontal stress in the region is orientated NE-SW, taken from the closest measurements in Turku (Pennala, 2017). The magnitude of the major horizontal stress ranges from 7 to 13 MPa and the minor stress from 3 to 7 MPa, between 10-20 m depth. Seismic activity recorded since 1610 has shown that no earthquakes greater than Mw 5 have been recorded (Ahjos et al., 1984). However, predictions of earthquakes with no historical magnitude limit indicate that a maximum of Mw 7.9 could be reached near Långören Island (Saari, 2000). Rantanen (2016) reported that the geotechnical properties of the microcline granite display similar characteristics to that of the Olkiluoto granite. A compilation of intact rock properties for Långören Island is listed in Table 4-1.

Table 4-1: Compilation of geotechnical parameters (petrophysical and strength limits) for microcline granite, taken from publications of similar rock units in the area.

Property	Value	Reference
Young's Modulus (E, GPa)	55	(Siren, 2011)
Poisson's ratio	0.2	
Unconfined Compressive Strength (UCS, MPa)	114	
Tensile Strength (σ_t , MPa)	12	
Density (kg/m ³)	2700	(Rantanen 2016, references therein)
Thermal Expansion Coefficient (1/K)	9×10^{-6}	
Thermal Conductivity (W/mK)	3.2	
Specific Heat Capacity (J/kgK)	689	

4.5 Data Collection

4.5.1 Laboratory Test

Several hand samples and a core sample were collected, as shown in Figure 4-5. The core sample was 321 mm in length and had a diameter of 69.3 mm (Figure 4-5a). This was the only cored sample that could be taken from the island. Additionally, one hand sample was suitable for Brazilian tensile testing, also shown in Figure 4-5b. These samples were used to measure the tensile strength (σ_t) and the ultrasonic measured compression (primary) wave velocity (P-wave), with depth and orientation. Subsamples were taken perpendicular to the major axis of the sample (A axis), using two samples per sub-coring. Two fractures were identified in the cored samples which are visible at 150 mm and 210 mm depth below surface (Figure 4-3c). These represent the fractures that propagated on the hottest day in July 2014.

Brazilian indirect tensile tests were conducted according to the ISRM (1978) suggested methods. The A axis samples were tested such that the tensile fracture would be induced parallel to the ground surface. According to Hoek and Martin (2014), there should be longer micro cracks, Griffith flaws, and tensile wing cracks in the horizontal plane than the vertical plane, due to the high horizontal stresses in the near surface. Depending on the micro crack density, the rock mass could be weaker in the near surface than at depth leading to a strength anisotropy. Hence, the tests were carried out with the focus on the orientation of the load (or transducer) to the expected cracks, to measure the rock parameters in a parallel (PA) and perpendicular (PE) direction to ground surface. The tests results are tabulated in Table 4-2.

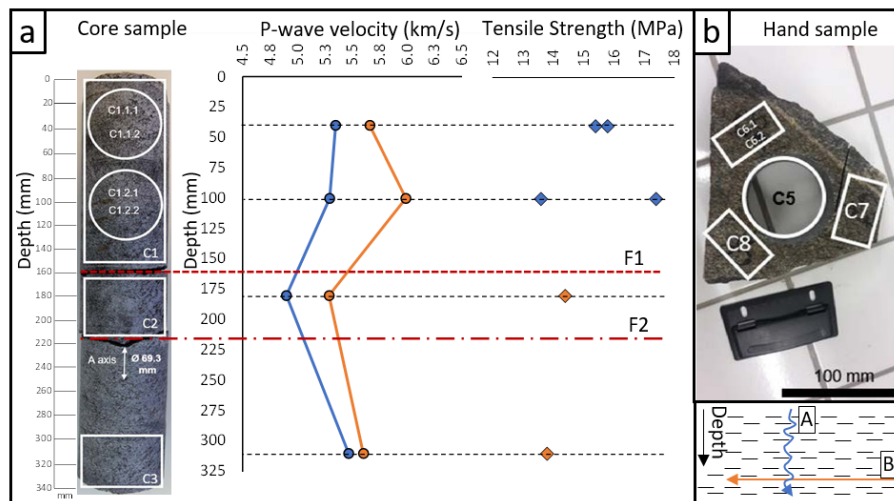


Figure 4-5: A a) cored sample and b) surface hand sample from Långören Island showing the specimen sections used for indirect Brazilian tensile testing and P-wave velocity measurements. Results for tests in A-axis (perpendicular to micro-cracks, PE) and B-axis (parallel to micro-cracks). Fractures F1 and F2 are highlighted in the plot. Data are listed in Table 3-3.

Table 4-2: Laboratory tests results for microcline granite samples from Långören Island. P-wave velocity and indirect Brazilian tensile testing were conducted in two orientations: A axis (vertical) which corresponds to PE (perpendicular to micro-cracks), and B axis (horizontal) as PA (parallel to micro-cracks).

Original Sample	Sample	Tensile Strength (MPa)		P-wave Velocity (km/s)	
		A-axis (PE)	B-axis (PA)	A-axis (PE)	B-axis (PA)
Core sample	C1	--	--	5.3	--
	C1.1.1	15.8	--	5.3	5.8
	C1.1.2	15.4	--	5.4	5.6
	C1.2.1	17.4	--	5.3	6.1
	C1.2.2	13.6	--	5.3	5.9
	C2	--	14.4	4.9	5.3
	C3	--	13.8	5.5	5.6
Hand sample	C5	--	8.6	--	--
	C6.1	10.5	--	--	--
	C6.2	12.9	--	--	--
	C7	15.2	--	4.7	5.9
	C8	13.9	--	4.7	5.8

The P-wave velocities for tests conducted in PE are consistently lower than the PA tests for the same sample. The PE velocities were between 5.3 to 5.4 km/s, whereas PA tests had more variable results between 5.5 km/s and 6.1 km/s. The lowest values were for sample C2, which lies between the two fracture surfaces and can be projected to the fresh fractures from 2014 (Figure 3-4c). The generally faster PA over the PE velocities is consistent with the theorized orientation of the micro-cracks. In the PE tests, if the micro-cracks are oriented parallel to the ground surface (i.e., perpendicular to the transducer), the wave must deviate from a straight path (i.e., shorter path). The more tortuous wave path slows the wave speed.

A smaller number of samples were tested for tensile strength, with the limitation to compare PA and PE orientation. The average tensile strength for PE tests is 14.3 MPa, where this is 12.3 MPa for PA tests. Generally, the results from the hand sample show a weaker strength (10.9 MPa in average), even lower than the minimum value of the core sample (i.e., C1.2.2: 13.6 MPa), regardless of the orientation. The indirect tensile strength and P-wave velocity measurements indicate a potential preferential orientation to the micro-cracks. However, the behaviour at depth can be only theorized with the difference between PA and PE that were 20% on average, as shown in the profile at depth in Figure 4-5a.

4.5.2 Initial Bedrock Temperature Variations

The preliminary data from the sensors is introduced in Figure 4-6, where the rock temperature at different depths is plotted. The temperature sensor at the shallowest position (0.04 m) shows the largest variation. The temperature of the rock mass in the near surface varies between 35°C and

15°C in July and August 2016. On the other hand, sensors at 1.00 m depth show a longer period of fluctuation, with temperatures consistently around 20°C. The temperature at 1.00 m is consistently lower than those sensors located at 0.44 m, however, the evening low air temperatures typically fall below the sub-surface rock temperature. The air temperature is the main driver in the temperature fluctuations, within the superficial layer, but other climatic factors, such as clouds, wind, and even tides (water temperature) could contribute to cooling processes in the area through convection and conduction.

The rock temperature is measured at two holes (Figure 4-3), to determine any differences between the temperature profile in a fractured and unfractured rock mass. These local variations might change the radiation (heat) absorbed into the rock mass from one location to another and contribute to increased thermal strains in one location over another. There is a significant temperature difference between the near surface (0.04 m) and lower 0.44 sensors as well as an offset in time for the peak temperature (see Figure 4-6). The fracture is acting as an insulator, reducing the amount of heat flowing from the surface into the rock mass.

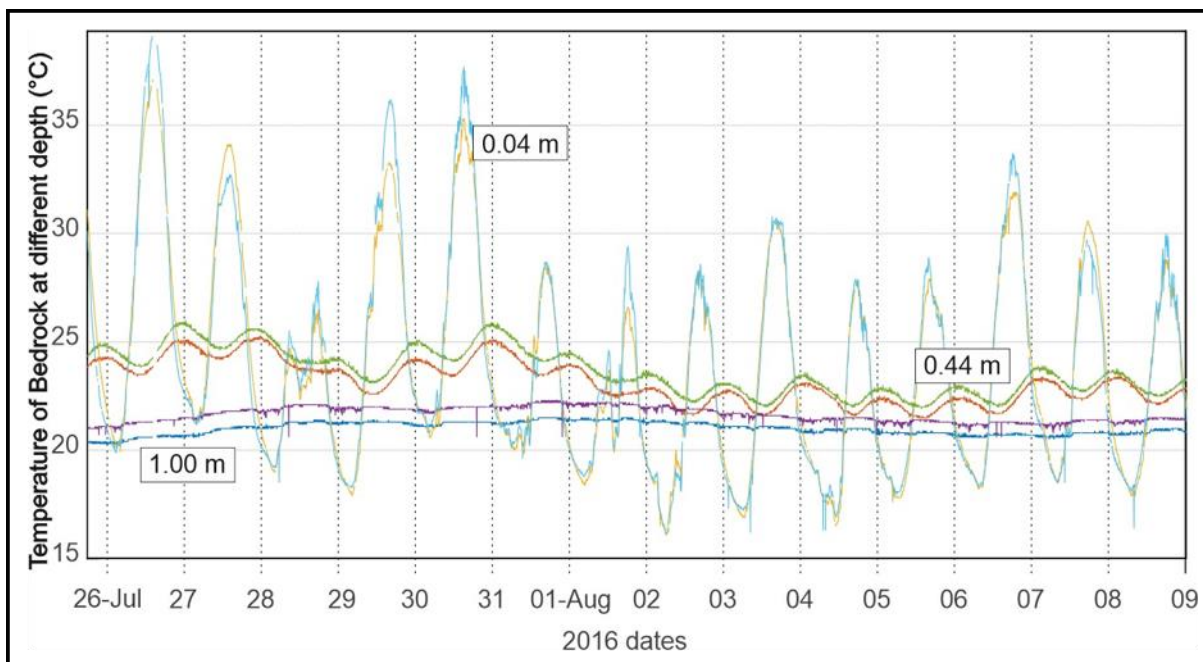


Figure 4-6: Temperature of bedrock at different depth for Långören Island. Data: July to August 2016 (Leith et al., 2017), grouped as yellow and light blue for sensors installed at 0.04 m deep, red and green for sensors at 0.44 m, and purple and blue for sensors at 1.00 deep.

4.5.3 Local Weather Conditions of Långören Island

The hourly weather conditions of the island were collected by the WS located in the area of interest at an elevation of 2 m above the ground. Because of the local environmental conditions of the

2014 cracking event were not captured (i.e. the WS began recording data from August 2016), the historical records from eight weather stations (see Figure 4-1 and Table 4-3) were gathered from the website of the Finnish Meteorological Institute (FMI), for the 2014 to 2019 period under hourly average observations (FMI 2021). In order to estimate the value of the local meteorological parameters at Långören Island, a 2nd order inverse distance weighting interpolation method (IDW2) was used with the data from the FMI to determine the time-series of air temperature (AT), wind speed (WSp) and solar radiation (SR) on an hourly basis. The IDW2 results were compared to the WS measured data, in order to estimate the time- series for the 2014 to 2019 period.

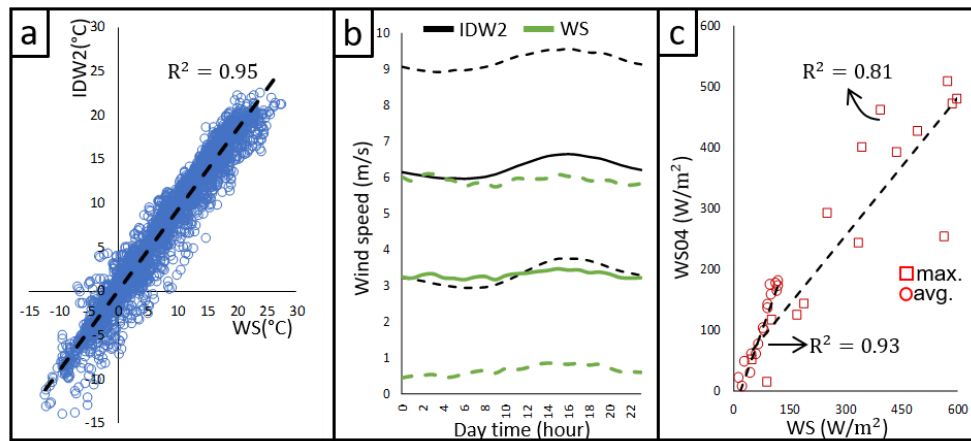


Figure 4-7: Local weather conditions of Långören Island, showing the correlation between estimated values from the IDW2 interpolation and locally measured by the weather station (WS) data for a) Air Temperature (AT). b) the average hourly values for Wind Speed (WSp), b) Solar Radiation values (SR).

Table 4-3: Weather stations used in the IDW2 interpolation, extracted from the Finnish Meteorological Institute open data (FMI 2021) The ID are associated with the locations in Fig. 1b. Lat.: Latitude, Long.: Longitude. The Year column indicates the oldest available datum. WS##: WS stands for weather station and ## indicates the station number adopted for this research purpose.

ID	Station Name	Latitude	Longitude	Year
WS01	Turku Rajakari	60.38	22.10	1991
WS02	Hanko Tulliniemi	59.81	22.91	1990
WS03	Kemiönsaari Vänä	59.87	22.19	1990
WS04	Parainen Utö	59.78	21.37	1881
WS05	Kökar Bogskär	59.50	20.35	1982
WS06	Lumparland Långnäs	60.12	20.30	2012
WS07	Kumlinge kirkonkylä	60.26	20.75	2000
WS08	Parainen Fagerholm	60.11	21.70	1989

Results for AT, WSp and SR are displayed in Figure 3-8. For the AT (Figure 4-7a), the IDW2 values and the WS data are well correlated ($R^2 = 0.95$), yet IDW2 tends to underestimate the AT for Långören Island by $\Delta 3^\circ\text{C}$. For the WSp, the average values per hour were compared (Figure 4-7b) which were defined as the average value and plus/minus standard deviation (i.e. three trends in the plot). It is seen that the upper band for the IDW2 data has greater speeds (9.5 m/s) than the average WS data (6.5 m/s). The $\Delta 3$ m/s difference remains constant for the average trend and the lower band as well between IDW2 and WS data. The IDW2 data set overlaps in its lower band with the upper band of the local WS, following both similar trends for the average hourly values throughout the day. For the solar radiation it was assumed that WS and WS04 (see Table 4-3) are close enough (50 km) to compare their acquired data, as shown in Figure 4-7c for daylight hours' measurements. When plotting the daily average values, those are better correlated ($R^2 = 0.89$) than daily maximum values ($R^2 = 0.81$), likely linked to local cloudiness. It is worth highlighting that solar radiation extends over a range from 90 W/m² to 690 W/m², whilst the average fluctuates from 20 W/m to 200 W/m².

4.5.4 Time-series of Local Weather and Rock Surface Temperature for Långören Island

The climatic data for Långören Island guides the thermal processes occurring on the rock mass and resulting in the rock surface temperatures. To this end, total heat flux (Q) acting on the rock surface was calculated using the approach from Bentz (2000). This involves the combination of radiation (Q_{rad}), convection (Q_{conv}) and conduction (Q_{cond}) thermal processes which are dependent on the rock properties and meteorological conditions as shown in Equation 4-1. It includes the climatic variable used in each Q component. Since the climatic data for Långören Island was constructed as time-series, the Q and rock temperature (RT) values are presented as time-series as well.

$$Q = Q_{\text{rad}} (\text{SR}, \text{AT}) + Q_{\text{conv}} (\text{WSp}, \text{AT}) + Q_{\text{cond}} (\text{AT}, \text{RT}) \quad \text{Equation 4-1}$$

The time-series for the island's weather conditions were constructed with the IDW2 data, filling in holes in the local monitoring record for Långören Island, shown in Figure 4-8. These data were calculated for the period of 2014 to 2019 to examine the weather influences prior to the first cracking event. The monthly average AT fluctuate between -5°C and 20°C (Figure 4-8a), whereas the weekly average of AT ranges from -6°C to 5°C for winter and 12°C to 22°C for summer. During the time that cracking events were registered, extreme high values of AT were recorded. In fact, AT above 30°C occurred in July 2014 and 2018, for 1 and 2 days, respectively, which are also shown in the AT time-series. The time-series for SR are introduced in Figure 4-8b an average of 90 W/m² (30 W/m² for winter and 150 W/m² for summer). The SR time-series reveals variations

throughout the year related to the island's latitude, influenced by the day-length (6 hours in winter and 19 hours in summer) and the incident angle of the sun (i.e. solar-path). Regarding time-series for WSp, they show a yearly average of 5 m/s (7 m/s for winter and 4 m/s for summer).

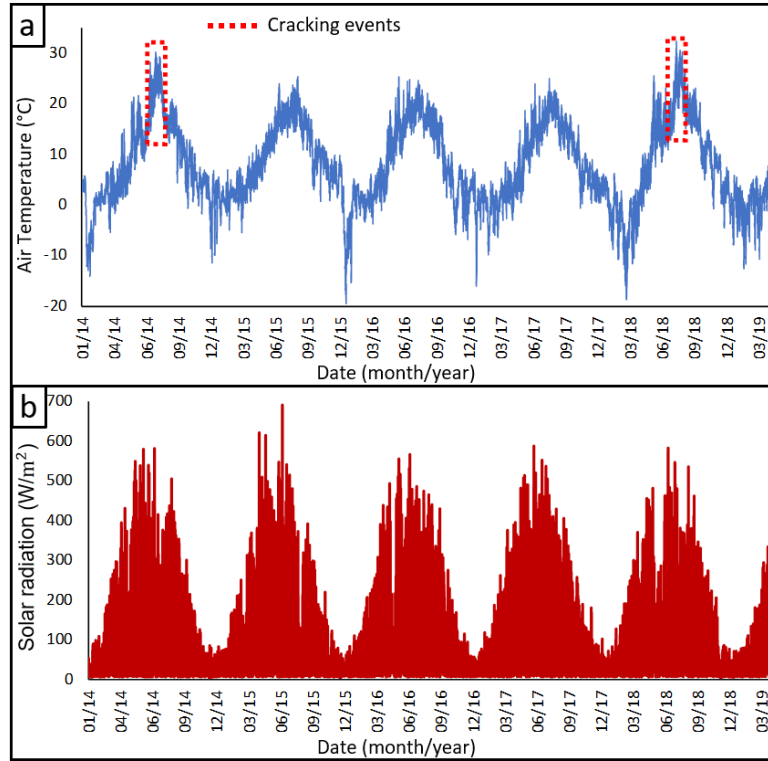


Figure 4-8: Time-series of thermal conditions for Långören Island, showing a) the air temperature (AT) with cracking events enclosed in dashed lines and b) the solar radiation (SR) received by the island. Values are presented in hourly (blue line) and monthly (black line) basis.

The Q time-series is plotted in Figure 4-9a, including the weekly average of the maximum and minimum values. Q values range between -200 W/m^2 to 200 W/m^2 for the summer season, whereas during the winter season the Q values are minimized to a range of -50 W/m^2 to 50 W/m^2 . The Q time-series allowed to calculate the rock temperature surface (RT_c) with the Carslaw and Jaeger (1959) approach for the period of 2014 - 2019, and assuming an initial rock mass temperature of 10°C . When comparing RT_c values with RT from observation in the area (Figure 4-9b), sensor at depth of 4 mm), both data sets yield similar seasonal trends. In fact, Figure 4-9c shows that the correlation results in an R^2 of 0.79 with the largest deviation being for RT measured above 20°C . Then, the RT_c time-series were transformed into sin functions (RT_f) to simplify the inputs for the TM simulations. The RT_f time-series was set so that the difference between maximum and minimum values for each day is 8°C , whereas the annual cycle has maximum values of 35°C in summer and 5°C winter (Figure 4-9d). The RT_f values are compared to

observations from Långören Island in Figure 3-10e, achieving an R^2 of 0.68. RTf is a key input in the numerical model in FLAC®.

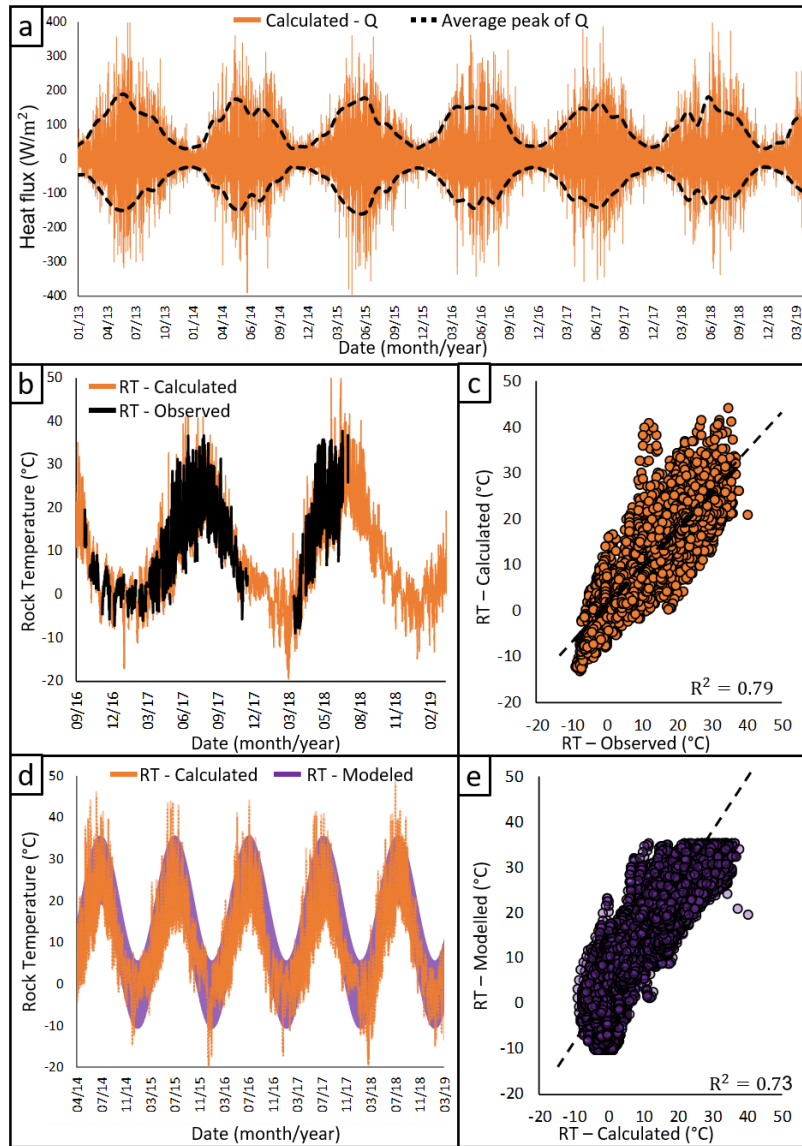


Figure 4-9: Time-series of heat flux and rock surface temperature for Långören Island. Values are presented in hourly (blue line) and monthly (black line) basis for a) The calculated heat flux (Q , with the use of Eqn.3-1) that helps in calculating b) the rock temperature (RT) time-series from Q and on-site measurements. c) The scatter plot of calculated rock temperature (RT_c) and measured RT show the correlation coefficient. d) The time-series plot of the calculated rock temperature (RT_c) and rock temperature functions (RT_f) for Långören Island from January 2014 to March 2019, are also correlated in e) a scatter plot of rock temperature functions (RT_f) and measured RT showing the R^2 value of the correlation.

4.6 Numerical Model

4.6.1 Numerical Model Setup

The case study was simplified into a 2D cross section (Figure 4-3b and Figure 4-10), with the aim to reproduce the vertical displacements measured across F1 and F2, with the focus on F2 during the observation period for comparison purposes. A two-dimensional numerical finite difference model was developed using Itasca's FLAC® software, for a coupled thermo-mechanical solution.

As an exploratory model, an elastic constitutive model for the rock mass in combination with thermal isotropic conditions was inputted. Properties for intact rock and discontinuities are listed in Table 4-4, which includes literature values from Table 4-1, the P-wave and tensile strength tests from Table 4-2 and joint properties for Fracture 1 and 2. Strength limits for intact rock were reported in two directions following the transverse isotropy of microcline granite, whereas the elastic and thermal properties are listed as isotropy behaviour from available data in the literature.

The strength of joints was calculated following Barton and Choubey (1979), with structural mapping and calibration from Rantanen (2016). Normal and shear stiffness values were determined using the approach outlined by Itasca (2019), which yielded a normal-to-shear stiffness ratio of 2.4. This ratio accounts for the planes' roughness, mineral exposure, and fresh surfaces resulting from the fracturing process, leading to relatively high shear stiffness. Additionally, a Geological Strength Index (GSI) of 75 was assigned to the rock surface, based on an assessment of the surficial weathering state and the overall rock mass condition on site.

Fractures F1 and F2 were modeled as unglued interfaces with fixed ends, allowing the sides of the fractures to open and close relative to one another, while preventing any shear displacement. Both interfaces were also set to transfer heat, meaning no thermal zones were considered null between the sides of F1 or F2.

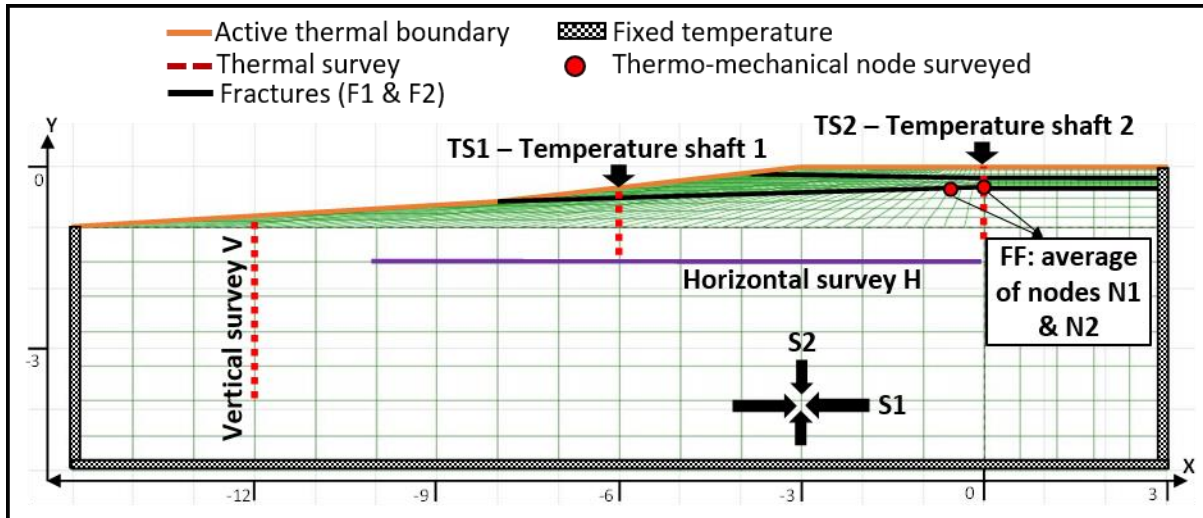


Figure 4-10: Cross section of the numerical model, indicating nodal and linear surveys, as well as grid size and fractures F1 and F2. The thermal boundaries (i.e. active and isothermal) are also indicated. TS1 and TS2 are vertical surveys emulating temperature shafts 1 and 2 respectively. V is a vertical thermal survey of a non-fractured area. FF are thermo-mechanical nodes that are surveyed close to TS1, their average vertical displacement leads to calculate CA.

The geometry of the area of interest was set with the origin at the surface level of TS2, as shown in Figure 4-10. The bottom boundary was defined at 5 m below the top of the highest point of the topographic surface in the model. Lateral and vertical motion restrictions were coded for the bottom boundary, whereas vertical boundaries were set with free movement in y-axis and restricted in x-axis. A thermal boundary was set on the upper boundary, using the RTf from Figure 4-9d. The vertical and bottom boundary were set with a fixed temperature of 10°C, which is also the rock mass temperature at the beginning of the simulation time. The initial RT of the rock mass does not impact the resulting RT throughout the simulation time since the model stabilizes thermally after 90 days of simulation. Therefore, an extra year was modelled to ensure thermal adjustment, yet elastic displacements were zeroed in January 2014 and after the model reached mechanical equilibrium. It is important to note that the grid was configured to a coarser zone density (zoning multiplier of 2x2) at the bottom and denser in the region above F2 (zoning multiplier of 6x6). External forces from seismic events or water pressure were not incorporated at this stage of modelling, although these may also influence the stability of the rock mass.

Table 4-4: Geotechnical and thermal properties of intact rock for numerical model. Some properties are reported in PA (parallel) or PE (perpendicular) orientation of the test with respect to the micro-crack orientation. Properties of discontinuities, calculated with equations from Barton and Choubey (1979). Discontinuities were modelled as unbonded interfaces in FLAC®, with fixed ends to allow only the opening and closing of the sides of the joints.

Material	Property	PE	PA	Reference
Intact rock	Tensile Strength (σ_t , MPa)	14.3	12.3	(Alcaino-Olivares et al. 2018)
	P-wave velocity (km/s)	5.2	5.8	
	Unconfined Compressive Strength (UCS, MPa)	123	105	
	Fracture toughness mode I (K_{IC} , MPa $\sqrt{m}$)	3.1	1.9	(Siren, 2011)
	Young's Modulus (E, GPa)	55		
	Poisson's ratio	0.2		
	Density (kg/m ³)	2700		
	Thermal Expansion Coefficient (1/K)	9 * 10 ⁻⁶		(Rantanen 2016,
	Thermal Conductivity (W/mK)	3.2		references therein)
	Specific Heat Capacity (J/kgK)	689		
	Solar absorption coefficient	0.8		(Zhao et al. 2019)
	Coefficient of emissivity	0.44		
Discontinuity	Joint normal stiffness (k _n , MPa/m)	45,000		Itasca (2019)
	Joint shear stiffness (k _s , MPa/m)	19,000		
	Cohesion (c, MPa)	1		Calculated with equations from Barton and Choubey (1979)
	Friction angle (φ , °)	50		
	Dilation angle (φ , °)	35		

4.6.2 Preliminary Results

The thermal results are reported as rock temperatures (RT) in the vertical orientation. To this end, nodal and linear surveys were made across the section shown in Figure 4-10. TS1 and TS2 are of interest to validate the simulated RT. Simulated data along TS1 and TS2 were plotted against measurements acquired from 2016 to 2018. Deviations in the range of 5°C for the measured RT are seen in comparison to the simulated RT in TS1 with an $R^2 = 0.76$ (Figure 4-11a). At TS2 (Figure 4-11b), this range spans from 5°C for low measured temperatures (between -10°C to 10°C) to 20°C for high measured temperatures (between 20°C to 33°C), achieving an overall R^2 of 0.65. In order to further understand the thermal behaviour of the rock mass, a time- series of the RT was conducted across the vertical linear survey at position V (Figure 4-10).

The location of this survey was selected away from the fractures and a similar distance from the boundary as TS2 is from the other vertical boundary. The heatmap for the V time-series is plotted in Figure 4-11c. Values were presented as the daily RT average, taking in account all simulated years, which may underestimate the peak values of RT in some instances, yet is still important to examine the depth of influence. The left axis shows the depth from the surface and the bottom axis indicates the time along the year per month. The maximum RT (i.e. 20°C – 30°C) are reached during summer months (i.e. mid-June to mid-September) at a maximum depth of 1.0 m, whereas the minimum RT (i.e. 0°C) occurs during the winter months (i.e. December to March), but reaching a shallower depth of 0.5 m only. Below 1.0 m depth, the RT is constant at 10°C across the modelled region and throughout the year. This result is consistent with the yearly average shallow ground temperature measured at Långören Island, which was set as the thermal boundary conditions.

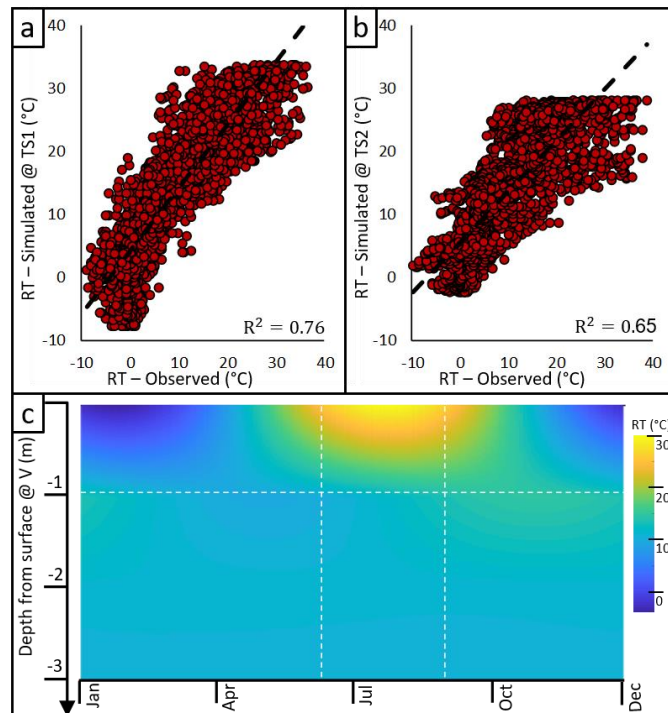


Figure 4-11: FLAC® thermal model results, with results for rock temperature measured at different points, such as a) scatter plot of measured and simulated RT values at TS1 and b) Scatter plot of observed and simulated RT values at TS2. Also, a c) Heatmap of RT across V throughout the year.

The mechanical results are expressed in terms of the crack aperture (CA) and determined in a similar manner to the actual crack meter used in the field. The numerical CA was calculated using the average vertical position (displacement) of two nodes located close to the F2 – TS2 intersection, termed as FF (Figure 4-12). The FF location is zeroed in January 2014, so that CA

changes are referred to this point. Positive increments of CA are indicative of the rock slab rising (i.e. crack opening) whereas negative increments are interpreted as contraction of rock slabs (i.e. crack closure). Results are expressed as time-series of the RT and CA, which are displayed in Figure 4-12a, including the air temperature time-series (see Figure 3-9). Simulated CA values show a cumulative crack extension from -0.3 mm in July 2014 to 1 mm in March 2019 (note CA was zeroed in January 2014, so both negative values mean closure). It is important to note that AT aligns with RT at FF ($R^2 = 0.62$), since RT at the landscape's surface is the result of the combination of AT, WSp and SR with the approach from Bentz (2000).

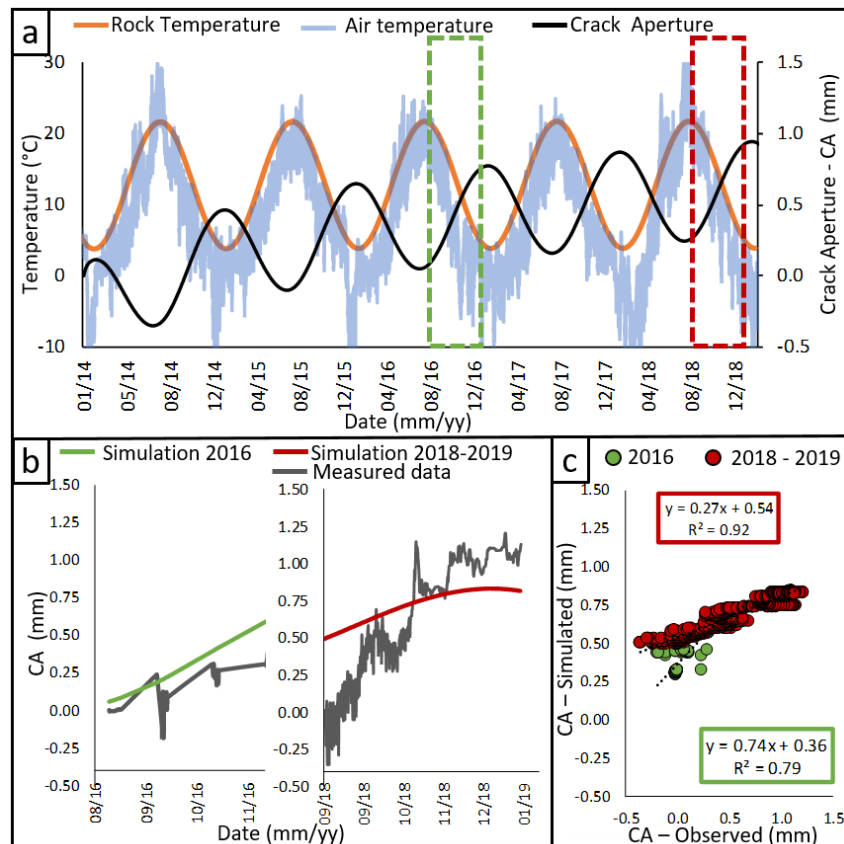


Figure 4-12: FLAC® thermo-mechanical model results, with a) time series of simulated results for RT, AT and CA at the FF nodes (see Figure 3-11) from 2014 to 2019. Green and red dashed line rectangles enclose periods where CA measured data are available. b) Time series of CA for simulated and measured data for 2016 and 2018 periods. c) Scatter plot of simulated and measured CA values at FF.

The simulation results for CA are compared with measurements recorded by the crack meter (see Figure 4-3) during four months in 2016 and six months in 2018- 2019 (see Figure 4-12b). Results for the 2018 – 2019 period showed that the simulated time-series have a gentler slope (0.1 mm/month) than measured CA (0.3 mm/month). The simulated mean value of CA is 0.65 mm whilst 0.5 mm were measured on average. The difference of the mean values ($\Delta 0.15$ mm) is

similar to the calculated one for the 2016 period. A scatter plot for both periods (2016 and 2018 – 2019) is shown in Figure 4-12c, where a linear relationship was used to represent the correlation between measured and simulated data. In 2016 the plot shows an R^2 of 0.8, whereas the 2018 – 2019 period the R^2 equals 0.9. However, both simulated data sets (i.e. 2016 and 2018 – 2019) seem to be shifted by +0.4 mm (average of both linear intercept) from the measured data. In addition, the simulated CA data have an average of 0.35 mm, which is similar to the shifting magnitude disclosed for the comparison. Therefore, the cumulative CA is achieved by the rock mass, and simulation in FLAC® can reproduce similar magnitude of values with the current model setup.

4.7 Analysis of Thermo-Mechanical Fatigue in Rocks

The exfoliation fracture theories with basis on pressure release (i.e. glacier movement and tectonic evolution) or surface-parallel compression (i.e. high horizontal stress which induces tensile stress), in combination with the dome-shaped topography of Långören Island, suggests that a bending moment concentration leads to crack formation (Rantanen, 2016). The author concludes that rock temperature fluctuation contributes in increasing the tensile stress on the dome-shaped surface, and increasing the stress intensity factor of the existing fracture such as the F1 and F2 propagation (and exhibiting fractured slabs). The combination of varying climatic conditions on Långören Island were required inputs for the model presented in our work to match the measured surficial temperatures, as also confirmed by other authors simulating the behaviour of other locations (e.g. Collins et al. 2018, Marmoni et al., 2020).

Analysis of the numerical model's results provided insights into the mechanical drivers of this thermal fracturing event. Rock surface temperatures were modelled and compared to data measured on the rock mass in Långören Island, with an R^2 of 0.7 for the shallow layers (i.e. 4 mm deep). The sections of the model located below 1.0 m from the surface are not greatly affected by thermal fluctuations (i.e. $\Delta 1^\circ\text{C}$) so little vertical displacements were recorded (i.e. $\pm 10^{-5}$ mm, no cumulative) during the simulation time. For the presented elastic scenario, both F1 and F2 fractures (interfaces) could move with normal displacements only (i.e. by fixing the ends of the interfaces, the shearing displacement was not allowed). Therefore, it is a matter of interest to observe how the F2 interface sides in the vicinity of TS2 are behaving in terms of CA for both measured and simulated data (Fig. 4f). Comparatively, the measured CA reported smaller values than the simulated CA in 0.4 mm. This relates to the simulated CA values accumulated between 2014 and 2016 (i.e. simulation time starts in January 2014) and the measured CA which just started in 2016.

Other differences between results and measurements can be associated with the model grid aspect ratio, especially in the region above F2 (see Figure 4-10) with large zoning distortion angles in the region between TS2 and TS1. However, the grid at this region was refined (i.e. zone multiplier) so that more zones became available to prevent generating artificial stress concentrations and strong gradients in small distances. Reducing the stress gradients result in more accurate displacements (Itasca Consulting Group, 2019). The grid quality is a crucial feature of the modelling stage on its own, as it directly influences and fast convergence, which contributes to deviations of the simulated results from measured values for Långören Island in this preliminary numerical study.

Nevertheless, the focus of this site investigation is to provide insights for modelling the cracking events of 2014 and 2018, our simulation results helped in conceptualizing the mechanism of thermo-mechanical fatigue acting at the F2 fracture. The fatigue crack growth under repeated load is the most common mechanism discussed by several authors to explain the action of environmental conditions in cracking rock masses in different geological and environmental scenarios (e.g. Collins et al. 2018, Alcaïno- Olivares et al. 2020, Marmoni et al. 2020). The TM results are plotted in Figure 3-14, linking ratios of CA and RT over the measured and simulated time-frame for F2. The CA rate for simulated data was in the order of 10^{-4} mm/hr. The CA measurements for 2016 resulted in a yearly average rate of $2 \cdot 10^{-4}$ mm/hr, and the 2018 – 2019 period was $4 \cdot 10^{-4}$ mm/hr. The RT rate for simulated data was $3 \cdot 10^{-3}$ °C/hr. The yearly RT rate for measurements of 2016 data was $9 \cdot 10^{-3}$ °C/hr and the 2018 – 2019 period was $6 \cdot 10^{-3}$ °C/hr.

In this research, the TM action is numerically defined by the ratio between CA and RT for the repeated thermal cyclic load. The measured data for F2 (Figure 4-13a) indicated monthly thermal cycles at different ratios for the same months of 2016 (0.02 mm/°C) and 2018 (0.06 mm/°C), likely linked to cumulative CA and propagation of F2 in the x-axis. Likewise, Figure 4-13b shows results for the simulated data with an average ratio of 0.03 mm/°C and 0.06 mm/°C for 2016 and 2018 respectively. The ability of F2 for opening/closing cycles is assumed to be linked to horizontal extension of F2. Therein, the CA relates to stress concentration leading to variations in the stress intensity factor (K_I) at the crack tip of F2 and its extension prior to 2018 (i.e. 1.5 m of existing rock-bridge at the west end). Under this conceptualization, the entire cracking event history of the site must be inputted in further modelling. In reality, there have been at least (i.e. registered and filmed) two events of surficial cracking (i.e. F1 in July 2014 and F2 in August 2018), which must be added as fracturing stages in future modelling. This will help elucidate the stress intensity factor history

at both fracture tips (i.e. F1 and F2), hence revealing the conditions to overpass the fracture toughness prompting cracking.

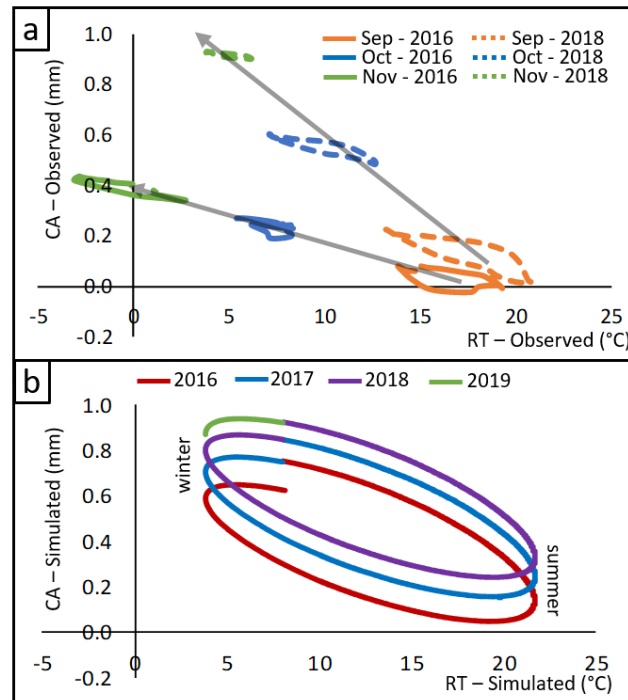


Figure 4-13: Thermo-mechanical cycles of CA as a result of RT. Values are displayed as the daily average. a) Observed data for 2016 and 2018 — 2019 periods. b) Simulated data from 2016 to 2019.

4.8 Lessons Learnt from Site Investigations and Preliminary Data

The dynamic fracturing event of 2014 on Långören Island represents a rare opportunity to study fracture growth that is not associated with the typical driving forces, such as gravity or stress change due to excavating. This is even enhanced with the 2018 cracking events, which allowed our research to track the fracture expansion and to test a prototype of the monitoring system. The lack of rainfall or other common climatic drivers and the fact that it was the hottest day on record all point to the potential hazard associated with increasing air temperature on the bedrock stability. The initial site investigation provided the methodology to examine TM fatigue in rock masses using measured data from the case study on Långören Island, Finland.

The laboratory data from samples gathered from Långören Island indicate a potential influence of the micro- crack orientation on the tensile strength and P-wave velocity. These micro-cracks represent important sites for continued fracture growth when the stress conditions reach the critical threshold. With substantial influence of the air temperature up to 0.44 m below the ground surface and large thermal changes on daily cycles, there is potential that either the bedrock strength is decreasing with time due to fatigue or that the thermal strain is enough to put the rock mass past

the critical fracture growth threshold. The measured data indicated an average TM deformation of $0.04 \text{ mm/}^{\circ}\text{C}$, whereas the simulated data delivered a ratio of $0.05 \text{ mm/}^{\circ}\text{C}$ for the F2 opening and closing cycles. It is conceptualized that these ratios are linked to horizontal extension of F2, hence to increments in stress distribution around the crack tip leading to ultimate TM fatigue.

The study of the time-series of the data from measurements and numerical modelling assisted with the the interpretation of the thermo-mechanical fatigue. As a result, a ratio for deformations for opening and closing cycles of the fractures becomes a key indicator to determine the fatigue limit of rocks. Nevertheless, the Långören Island research involved several challenges with the data acquisition that limited the capturing of the rock mass response. For instance, the monitoring system operated from July 2016 to March 2019, with three scheduled maintenance trips. However, only 10 out of 34 months were recorded, with the missing data attributed to power disruptions or system disconnections. A more completed data acquisition would have improved the calibration of models to better explain the rock fracturing process. However, maintaining the system at Långören Island proved too costly and logistically challenging, with no continuous support on-site, requiring significant personnel, equipment and coordination to keep the system operational. As a result, in March 2019, a final campaign was conducted. No new fracturing was observed, and the site appeared to have reached an equilibrium, with no further fracturing expected likely until a new cycle of high temperatures. This led to the decision to uninstall the monitoring system and abandon the site.

The outcomes from the Långören Island study provided valuable insights into monitoring strategies and the capability of the modeling software to replicate measured data from thermo-mechanical cycles. Challenges encountered at Långören Island, particularly those related to power, connectivity, and cabling, were addressed during the instrumentation installation of the Valley of the Kings (Egypt). While the Valley of the Kings case still experienced periods of missing data, sometimes lasting several months, general trends could still be identified. The lessons learned from Långören Island, such as calculating rock surface temperatures, defining thermal boundaries, and coding the geometry, proved essential in streamlining the modeling process for the Valley of the Kings.

Additionally, the absence of water at the Valley of the Kings, where rain is rare and typically catastrophic when it occurs (Theban Mapping Project, 2005), allowed the study to focus exclusively on thermo-mechanical fatigue driven by temperature fluctuations from solar radiation and wind. This presented a unique opportunity to isolate temperature-driven processes without interference from moisture-induced fracturing. It is important to note, however, that this situation

could be disrupted by episodes of flash flooding, which may induce swelling and shrinking in the rock mass, leading to additional damage. Such events were not encountered during the study period. As a result, the methodology developed for Långören Island was applied to the Valley of the Kings with more extensive discussion, owing to the larger volume of data collected in Egypt.

CHAPTER 5 ROCK MECHANICAL LABORATORY TESTING OF THEBES LIMESTONE FORMATION (MEMBER I), VALLEY OF THE KINGS, EGYPT

5.1 Preface

The following chapter presents the rock mechanical laboratory analyses of the study case in the Valley of the Kings (KV), Egypt, and provides a summary of the geotechnical rock intact parameters for four units of the Theban Mountains. Since the lack of formal documentation for geotechnical properties from the KV, the study is relevant to further input numerical models of rock stability, particularly in the rock column above tomb KV42. These tests are not only the first exhaustive documentation of intact rock properties for the marly and micritic limestone from the Member I of the Thebes Limestone Formation but also provides a first analysis of crack initiation stress thresholds, which are important properties for long-term stability considerations. The final document was published in *Geotechnics* in 2022 as follows:

Alcaíno-Olivares, R., Ziegler, M., Bickel, S., Ismaiel, I., Leith, K., and Perras, M. (2022) Rock Mechanical Laboratory Testing of Thebes Limestone Formation (Member I), Valley of the Kings, Luxor, Egypt. *Geotechnics* 2 (4), pp. 825–854. <https://doi.org/10.3390/geotechnics2040040>

The contribution of the authors are: **conceptualization** (Alcaino-Olivares, Ziegler and Perras), **data curation** (Alcaino-Olivares and Perras), **formal analysis** (Alcaino-Olivares, Ziegler, Ismaiel and Perras), **funding acquisition** (Ziegler, Bickel and Perras), **investigation** (Alcaino-Olivares, Ziegler, Perras), **methodology** (Alcaino-Olivares, Ziegler and Perras), **project administration** (Bickel), **resources** (Ismaiel), **writing-original manuscript** (Alcaino-Olivares) and **writing-review and editing** (Ziegler, Perras, Ismaiel, Leith and Bickel).

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5.2 Abstract

The Thebes Limestone Formation of Lower Eocene age is one of the most extensive rock units in Egypt. It is of importance to the apogee of the ancient Egyptian civilization, particularly in Luxor (South-Central Egypt), where the rock formation hosts the Theban Necropolis, a group of funerary chambers and temples from the New Kingdom Egyptian era (3500–3000 BP). In this work, we investigated the petrophysical and rock mechanical properties (e.g., rock strength, critical crack stress thresholds) through laboratory tests on eleven rock blocks collected from one area within the Theban Necropolis known as the Valley of the Kings (KV). The blocks belong to Member I of the Thebes Limestone Formation, including six blocks of marly limestone, three blocks of micritic limestone, one block of argillaceous limestone from the Upper Esna Shale Formation, and one block of silicified limestone of unknown origin. Special attention was given to the orientation of bedding planes in the samples: tests were conducted in parallel (PA) and perpendicular (PE) configurations with respect to bedding planes. We found that the marly limestone had an average unconfined compressive strength (UCS) of 30 MPa and 39 MPa for the PA and PE tests, respectively. Similarly, the micritic limestone tests showed an average UCS of 24 MPa for the PA orientation and 58 MPa for the PE orientation. The critical crack thresholds were the first ever reported for Member I, as measured with strain gauge readings. The average crack initiation (CI) stress thresholds for the marly limestone (PA: 14 MPa) and the micritic limestone (PA: 11 MPa; PE: 24 MPa) fall within the typical ratio of CI to UCS (0.36–0.52). The micritic limestone had an average Young's modulus (E) of 19.5 GPa and 10.3 GPa for PA and PE, respectively. The Poisson's ratios were 0.2 for PA and 0.1 for PE on average. Both marly and micritic limestone can be characterized by a transverse isotropic strength behaviour with respect to bedding planes. The failure strength for intact anisotropic rocks depends on the orientation of the applied force, which must be considered when assessing the stability of tombs and cliffs in the KV and will be used to understand and improve the preservation of this UNESCO World Heritage site.

5.3 Introduction

The Valley of the Kings (KV) is an ancient cemetery used by the Egyptians of the New Kingdom (3500–3000 BP) within a larger archaeological complex called the Theban Necropolis. The Theban Necropolis was constructed at the West Bank of the Nile River in Luxor, South-Central Egypt (Figure 5-1), and it has more than 450 underground tombs in an area of about six square kilometers. The area was declared a UNESCO World Heritage Site in 1979 and includes several sacred areas such as the Valley of the Queens, Sheikh Abd el-Qurna, Deir el-Medina, the Hatshepsut temple, Deir el-Bahari, and the KV. The KV was constructed for pharaohs' funerary rites, and 64 underground tombs have been discovered within the KV to date (Theban Mapping Project, 2005).

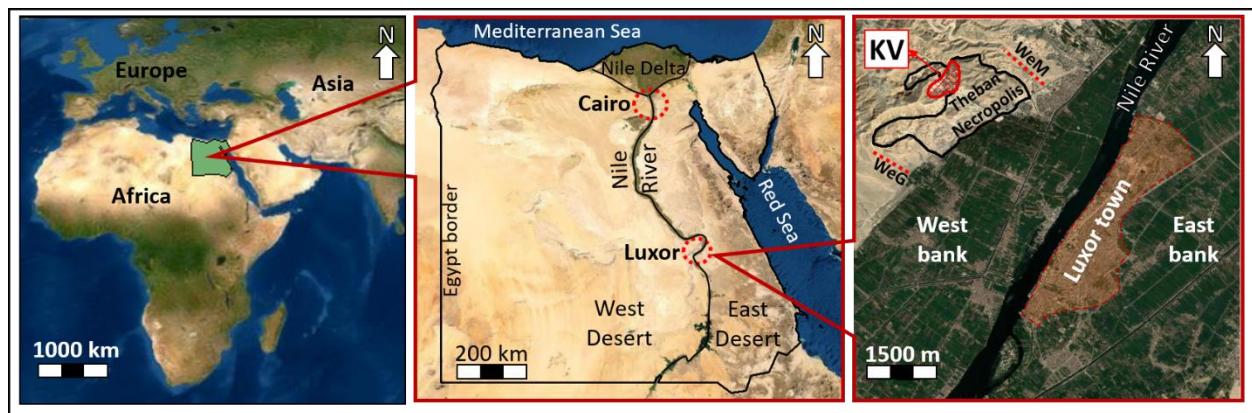


Figure 5-1: Geographical location of the Thebes Necropolis within Luxor, Egypt, with red hashed area indicating the Valley of the Kings (KV), and WeG and WeM stand for Wadi Gabbanat el-Gouroud and Wade el-Machtar, respectively.

Among many topics, geoarchaeology and environmental archaeology examine damage to rock caverns, tomb stability, geological hazards within ancient sites, and environmental influences on ancient art and archaeological artefacts (Hemeda 2021, Sesana et al. 2021, Bakun-Mazor 2013). Archaeological campaigns at the site strive to understand, document, and preserve the legacy of this ancient Egyptian civilization. Their work is supported by geologists that have undertaken research in the wider Theban Necropolis (Theban Mapping Project 2005, Rutherford 1988, Hamada et al. 2004, Tawfik et al. 2011, Dupuis et al. 2011, Aubry et al. 2009, Bardají et al. 2017, Ziegler et al. 2019). Within this context, the Swiss Kings' Valley Project of the University of Basel has been granted permission by Egyptian authorities to explore twelve tombs from the 18th to 25th Dynasties (i.e., 3500–2650 BP) situated in the central area of the KV. The main activities of this project are the detailed documentation and publication of the tombs' state (The King's Valley Project, 2017).

In addition, researchers wish to understand how to preserve a site, studying its critical state, potential mitigations, and enhancement through the use of an engineering geology methodology. Here, a joint geological team aids the Kings' Valley Project and comprises members from York University (Toronto, ON, Canada), ETH Zurich (Zurich, Switzerland) and South Valley University (Qena, Egypt). Our team assessed the current condition of the cliffs around the valley to determine their stability, triggering agents for rock falls, and (in particular) the effect of climatic conditions on the evolution of rock damage in subvertical cliffs of marlstone and limestone belonging to Member I of the Thebes Limestone Formation (Alcaino-Olivares et al. 2020, Lukovic et al. 2021).

The assignment of the Thebes Limestone in the stratigraphic nomenclature within the Theban Necropolis has recently come into question. Some authors have delineated a so-called Thebes Limestone Group, which includes the Serai Formation (Said, 1990). The Serai Formation would dominate the landscape of the Theban Necropolis, including Member I in the KV. Other authors described that the Thebes Limestone Formation comprises the Member I and associated outcrops in the Thebes Mountains (King et al. 2017). For the purpose of this research, the definition proposed by King et al. (2017) was used, which considers the Thebes Limestone Formation as independent of a stratigraphic group.

The Thebes Limestone Formation is one of the most extensive rock outcrops in Egypt, extending from the western bank of the Nile River to Kharga Oasis in the Western Desert, and it hosts world-class archaeological sites. However, only limited information regarding rock mechanical properties including anisotropic behaviour is presently available, as summarized in Table 5-1, and critical crack stress thresholds are missing. Although many geotechnical properties have been reported from various locations within the Theban Necropolis, typically the values are based on a small number of tested samples (between one to seven), whereas we have tested between 10 to 50 samples for each property. Here, we present results from a rock mechanical investigation of Member I of the Thebes Limestone Formation in which the entrance of the KV tombs were constructed. These results include physical rock properties (e.g., bulk density, compressional wave speed, thermal conductivity, heat capacity, connected porosity, slake durability, elastic properties), peak strength limits (tensile, and compressive), and critical crack thresholds (crack closure and crack initiation). We followed suggested methods from international standards, so that these data can support future analyses of the rock mass behaviour of natural and built structures of the KV, therefore contributing to the future preservation of this UNESCO world heritage site.

Table 5-1: Summary of reported values for geotechnical properties of rock units present in Theban Necropolis, including the average (Avg.), standard deviation (Std. Dev.), minimum (Min.) and maximum (Max.). Where values or factual information are not explicitly reported a blank entry is left in the table, normally indicated with *. Worth noting that authors reported range of values however no number of samples associated with these ranges. WV stands for West Valley of the Kings, whilst KV symbolises the East Valley of the Kings. KV# refers to a tomb within KV (e.g. KV17 is tomb 17 within KV). Wadi el-Machtar and Wadi Gabbanat El-Gouroud are gullies near the KV within Theban Necropolis, but they are not archaeological sites (see Figure 5-1a).

Property	Reference	Rock Type	Sampling location	Type of Test	#	Avg.	Std. Dev.	Min.	Max.
Rock Density (kg/cm ³)	Lazar (1995)	Chalk, Marl	Wadi El-Machtar	Buoyancy in Hg	13	2280	210	1950	2650
	Wüst (1995)	Limestone and Marl	Wadi Gabbanat El-Gouroud	Buoyancy in Hg	8	2100	200	1710	2210
	Wüst and Schlüchter (2000)	Marls, Member I	KV17	Possibly from Wüst (1995)	6	2150	70	2050	2180
Unit Weight (kN/m ³)	Hemeda (2018)	Marly limestone	KV5			20		20	21
Porosity (%)	Lazar (1995)	Chalk, Marl	Wadi El-Machtar	Δ grain and bulk ρ	13	13.4	8	1.1	27.5
	Wüst (1995)	Limestone and Marl	Wadi Gabbanat El-Gouroud	Grain ρ measured with	8	19.7	6.5	14	34.7
	Wüst and Schlüchter (2000)	Marls, Member I	KV17	multipycnometer	6	18.2	3.4	15.2	23.4
Apparent Porosity (%)	Hemeda (2018)	Marly limestone	KV5					14	19
Uniaxial compressive strength (UCS) in PE (MPa)	Lazar (1995)	Chalk, Marl	Wadi El-Machtar	UCS test	10	53	16	22.8	68.2
	Wüst and McLane (2000)	Marl	KV17	UCS test	1	78.2			
	Hemeda (2018)	Marly limestone	KV5					6	7
	Maissen (2019)	Micritic limestone (weathered)	Exterior KV42	Rebound hammer	4	40	7		
	Hemeda (2021)	Marly limestone	KV57	UCS test	7	8.7		8	9.3
UCS in PA (MPa)	Lazar (1995)	Chalk, Marl	Wadi El-Machtar	UCS test	7	35	10	16.2	47.8
	Maissen (2019)	Micritic limestone (weathered)	Exterior KV42	Rebound hammer	4	32	6		
P-wave speed (V_p) in PE (km/s)	Lazar (1995)	Chalk, Marl	Wadi El-Machtar	Transducer 100 kHz	3	2.36	0.24	2.2	2.7
	Maissen (2019)	Micritic limestone (weathered)	Exterior KV42	Transducer 54 kHz	4	2.95	0.5		
	Hemeda (2021)	Marly limestone	KV57	ASTM 597				0.7	0.9
V_p in PA (km/s)	Lazar (1995)	Chalk, Marl	Wadi El-Machtar	Transducer 100kHz	3	3.32	0.05	3.3	3.4
	Maissen (2019)	Micritic limestone (weathered)	Exterior KV42	Transducer 54 kHz	4	3.15	0.2		
S-wave speed (V_s) in PE (km/s)	Hemeda (2018)	Marly limestone	KV5	ASTM 597				0.7	1
Tensile strength (σ_t) (MPa)	Aydan et al. (2008)	Marly limestone	WV22	Tensile test *				4.4	5.1
	Dziedziec and Michiewicz (2018)	Marly limestone	Hatshepsut Temple	Beam test	4	2.95	0.26	2.7	3.4
Static elastic modulus, E-static (GPa)	Hemeda et al. (2018)	Marly limestone	KV5	UCS tests *		10			
	Aydan et al. (2008)	Soft limestone	WV22	UCS tests *				2	10
	Hemeda (2021)	Marly limestone	KV57			12			
Poisson's ratio (ν)	Abdallah and Helal (1990)	Limestone (Marly)	Hatshepsut Temple			0.21			
	Ayman (2013)	Limestone (Esna Shale Fm.)	KV17 Deepest Tunnel			0.2			
	Hemeda (2018)	Marly limestone	KV5					0.28	0.30
	Hemeda (2021)	Marly limestone	KV57					0.25	0.30
Max. axial strain (ϵ_{axial})	Wüst and McLane (2000)	Marl	KV17	UCS test	1	0.42%			
	Abdellah et al. (2017)	Limestone (Marly)	Hatshepsut Temple	Blocks of 30 mm	1	6%			
	Mohammed et al. (2019)	Limestone (Marly)	Hatshepsut Temple	tested at 1 mm/min	1	2.2%			

5.4 Rock Formations and Morphology of the Valley of the Kings

The Theban Necropolis is located on the West Bank of the Nile River. The site is at the base of the el-Qurna mountain of 478 m maximum elevation. Two marine sedimentary formations dominate the geology: Thebes Limestone Formation of Lower Eocene age (King et al., 2017), and the underlying Esna Shale Formation of Upper Paleocene/Lower Eocene age (Said, 1990). The Thebes Limestone Formation has a maximum vertical extent of about 340 m and is exposed at most of the cliffs surrounding the Theban Necropolis. Regionally, it is one of the largest formations, covering approximately 200,000 km² (King et al., 2017). At el-Qurna mountain, distinct subvertical cliffs and less steeply dipping slopes in between showcase the Thebes Limestone Formation's subunits of different mineralogical compositions, comprising fine-grained and thinly bedded micritic limestone, chalky and cherty with rare shale (Conoco Inc., 1986). The lower section of the Thebes Limestone Formation, i.e., Member I, was deposited in an open ocean shallow environment with high plankton production rates. Their original bedding orientation deviates at places between 20° and 40° (King et al., 2017), marked by the presence of chert nodules and chert layers aligning parallel along bedding planes in the upper units of Member I. The nature of bedding planes causes anisotropic rock behaviour (e.g., strength and deformation) (Lazar 1995, Wüst 1995, Hemeda 2018, Wüst and McLane 200). The Esna Shale Formation is exposed at the entrance area of the KV, in some undecorated rock tombs, as well as at slumped blocks that shape the landscape in the hills of Sheikh Abd el-Qurna (Ziegler et al. 2019, King et al. 2017).

The northern area of the Theban Necropolis is part of a wadi system in the Theban Mountains containing the East Valley and West Valley. Most royal tombs are located in the East Valley, known as the KV (Figure 5-2a). The KV is surrounded by steep cliffs of up to 30 m in height (Figure 5-2b) and small hills with gentle slopes. Other important features were described by Lukovic et al. (2021) and include low slope angles from the crest of cliffs to the upper plateau, overhanging blocks in cliff walls, gullies crossing the valley, and branching channels used as tourist paths dipping towards the north (<10°). Lukovic et al. (2021) also reported bedding angles from subhorizontal (15°) for unfaulted sections to steep angles (30°) for those affected by listric faults. The current morphology is a result of the tectonic fracture network, allowing for rock falls and slides, as well as repetitive fluvial erosion, cycles of flooding, and colluvium accumulation. The rock mass wasting processes accumulate rock debris (consolidated and loose) at the toe of the cliffs and the central site of the valley; these debris are transported by fluvial processes and redeposited during archaeological excavations (Cross, 2008).

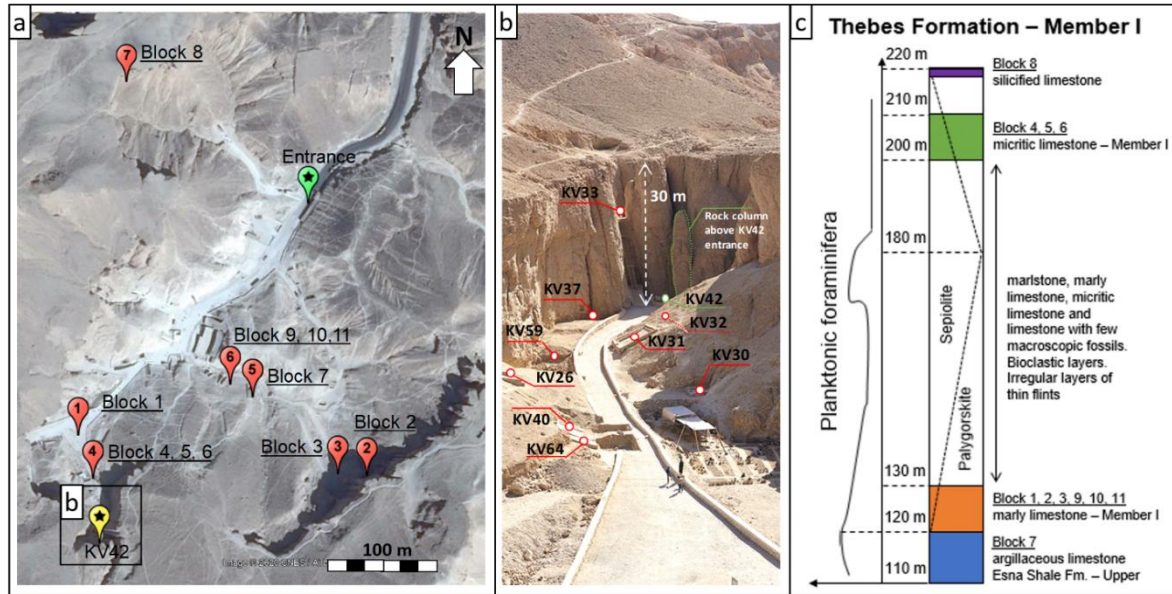


Figure 5-2: Introduction to the Valley of the Kings and the study area. (a) Satellite picture taken from Google Earth Pro (2021); imagery date 11 February 2018, showing the location of origin of the block samples (Block #) marked on the map. (b) Photograph of the southern branch of the valley at the University of Basel's excavation area, with marks (KV#) showing the tomb entrances (picture faces south). Tomb KV42 has a rock column located directly above the tomb's pit entrance, outlined in green (c) Stratigraphic column of Member I—Thebes Formation. The upper region of Esna Shale was added to describe block 7.

Member I of Thebes Limestone Formation dominates the exterior landscape of the KV and the entrance of the tombs. However, it is difficult to note the presence of Member I at the central section of the KV because of an accumulation of debris, colluvial materials (angular in shape; formed during flooding with limited length of transport), and finer gravel and aeolian sediments. This debris has caused a rise of the ground surface of up to 10 m in some areas within the KV (Lukovic et al. 2021, El Salam 2002). Conversely, the upper Esna Shale Formation is only visible at the entrance to the KV and in some of the deepest tombs, such as KV20, KV17, and KV7 (Aubry et al., 2009). The upper members of the Esna Shale Formation are water-sensitive rock units (i.e., high contents of smectite and illite) (Wüst and McLane 2000, Gelany et al. 2019). Outside of the KV, the Esna Shale Formation is the origin of most of the soils in both banks of the Nile River at Luxor. Outcrops of the Esna Shale Formation are found at some locations in the Theban Necropolis (e.g., Sheikh Ab el-Qurna, Hatshepsut temple, and Deir el-Medina) and at rock walls surrounding the main road leading to the KV.

King et al. (2017) provided a stratigraphic column for the Thebes Limestone Formation, including 13 subunits. The authors characterized the lower section of the Thebes Limestone Formation (up to 223.5 m.a.s.l.), also called Member I. Different subunits of marly limestone, marlstone, and

micritic limestone and layers of thin flints, cherts, and nodular limestone comprise Member I. A general mineralogical breakdown for Member I is about 60% calcite, <5% quartz, <10% ankerite, and 25–30% clay minerals (15% fibrous clay and 15% other clay minerals) (King et al., 2017). The clay mineral fraction of the rocks in Member I consist of sepiolite, palygorskite, and illite-smectite mixed-layer clay minerals. The latter was termed ISRo by King et al. (2017), and it is characterized by its high potential for expansion when in contact with water. The ISRo composition is dominated by smectite (85%), with illite reaching a maximum of 15% in the upper levels of the Thebes Formation (i.e., Member IV and V).

The presence of ISRo varies across the stratigraphic column in the Thebes Formation. At the lowest level of Member I (i.e., up to 125 m.a.s.l), ISRo dominates over 60% of the clay composition. Above this point in the stratigraphic column, the amount of planktonic foraminifera reduce, changing the ratio between sepiolite and palygorskite as shown in Figure 5-2c. The ratio of sepiolite to palygorskite has important implications in characterizing the depositional environment in which the units were formed (Wüst and McLane, 2000). However, it also explains the existence of manganese dendrites in some marly limestone belonging to Member I. Palygorskite tends to oxidize and supports as catalyst the formation of manganese dendrites in shallow surfaces, assisted by repeated cycles of wetting and drying (Wang et al., 2019). Both clay composition and grain size are important diagnostic features to determine the original location of different loose rock blocks in the KV and this was used in this study.

5.5 Sampling and Rock Description

Eleven rock block samples were collected at different locations within the KV (Figure 4-2a) during a field campaign in February 2019. The blocks were approximately 50 cm × 50 cm × 25 cm in size, as shown in Figure 5-3a. Since the KV is a UNESCO World Heritage Site, samples were selected from loose, partly excavated debris in order to not disturb or alter archaeological sites. We macroscopically inspected the blocks on-site to ascertain whether they belonged to Member I of the Thebes Limestone Formation (Table 5-2) by ensuring that blocks had sharp edges and corners (i.e., short transport distances from upper levels), a low fossiliferous content (fossils are rare in Member I) and did not show the effects of human influence (likely moved from other sites or interior of tombs). We also collected one block sample from the Esna Shale Formation and one block sample of silicified limestone. Block samples were described in accordance with BSI (2015). The estimated stratigraphic positions of samples are presented in Figure 5-2c. These data were compiled from information provided in the literature and on-site observations (King et al. 2017, Wüst and McLane 2000).

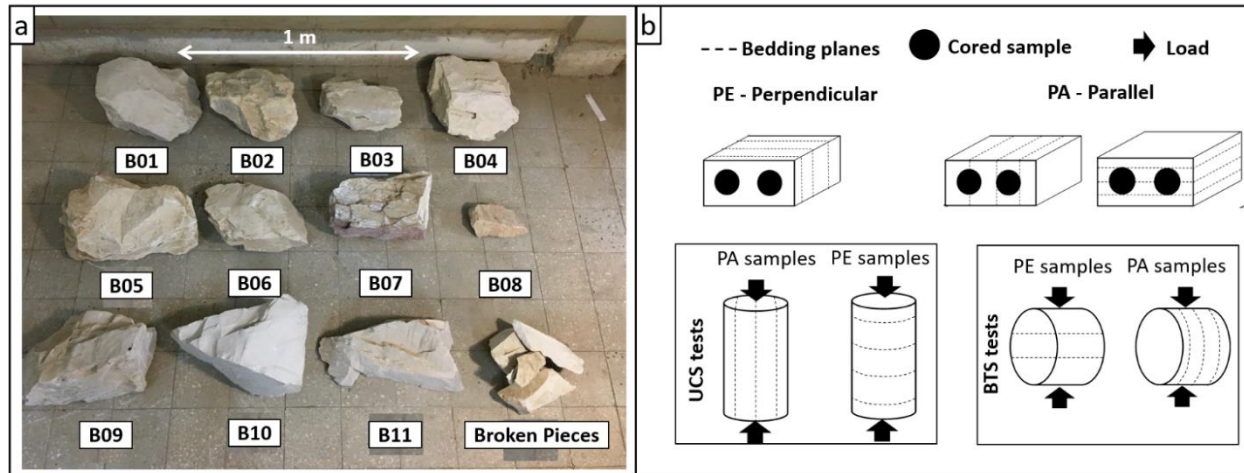


Figure 5-3: Sample preparation considerations followed in this research, showing (a) picture of all rock blocks collected from the KV during the field campaign in February 2019 (locations highlighted in Figure 4-2a) and (b) a sketch of the nomenclature to define Parallel (PA) and Perpendicular (PE) orientations of coring, as well as a sketch to show the loading direction for Unconfined Compressive Strength (UCS) and Brazilian Tensile Strength (BTS) tests. BTS tests were conducted only in PE, for 2 configurations of loading and anisotropy orientation.

Table 5-2: List of blocks collected from the KV for the present work grouped by the rock units. Descriptions based on macroscopical features.

Block	Formation	Elevation *	Rock Unit Description
8	Unknown **	220–223.5 m	Strong, massive, dark brown silicified limestone.
4, 5, 6	Thebes Fm.— Member I	200–210 m	Medium strong, thinly bedded, cream, micritic limestone. Discontinuities: closely spaced, from 45° to 90° from bedding planes, smooth, tight.
1, 2, 3 9, 10, 11	Thebes Fm.— Member I	120–130 m	Strong, very thinly bedded, light grey, marly limestone with manganese dendrites on shallow surfaces. Discontinuities: very closely to closely spaced, from 45° to 90° from bedding planes, smooth, tight to tight with small amount of clay infills.
7	Esna Shale Fm.	110–120 m Boundary with Thebes Fm.	Medium strong, thickly laminated, reddish brown mottled light grey argillaceous limestone. Discontinuities: closely spaced, from 90° to 70° from bedding planes, rough, tight with small amount of clay infills.

The marly limestone blocks (B1, B2, B3, B9, B10, and B11) showed an expansive response in contact with water, likely linked to a high content of ISRo minerals as described for the bottom section of Member I (120–130 m.a.s.l.), as well as the absence of interbedded flint layers and the presence of manganese dendrites at the outer layers (i.e., oxidation of palygorskite). Sample B7 was excavation material from KV17, so that is derived from the Esna Shale Formation. This had an argillaceous and oxidized appearance (i.e., reddish edges), and expanded in contact with water (i.e., stronger action than marly limestone blocks). The KV17 tomb is one of the deepest tombs, located at a transition between Member I of the Thebes Limestone Formation and the Esna Shale Formation, so the B7 sample was assigned to the Upper Esna Shale Formation (i.e., 110–120 m.a.s.l.). The micritic limestone samples (B4, B5, and B6) were

assigned to the upper levels (200–210 m.a.s.l.) of the stratigraphic column (Figure 5-2c) because of their relatively low expansion in contact with water (i.e., lower content of ISRo minerals), lack of manganese oxide dendrites on outer layers, low bioclast percentages (at naked eye), and presence of chert beddings. The silicified limestone sample (B8) was assumed to belong to the top of Member I (220–235 m.a.s.l.), as noted by Wüst (1995): “silicified reworked limestone band on top of Member I”; however, this was not explicitly reported by King et al. (2017). Following field collection, the samples were stored for one year at room temperature, isolated from direct sun exposure, and isolated from water contact. Laboratory tests were conducted in February 2020.

5.6 Methodology

The aim of the laboratory testing program was to geotechnically characterize the rock units while considering the natural anisotropy originating from rock bedding. The orientation of the tests relative to bedding plane orientations followed the nomenclature set out by Lazar (1995) and Wüst (1995), as illustrated in Figure 5-3b. The parallel (PA) and perpendicular (PE) orientations refer to the orientation of tests, so geotechnical properties are measured in PA and PE with respect to bedding planes. All tests and preparations of samples were carried out at room temperature and humidity in daylight hours during February 2020 in Qena, Egypt.

5.6.1 Rock Block Tests and Drilling of Rock Blocks

5.6.1.1 Thermal conductivity and volumetric specific heat

A thermal property analyzer was used (KD2 Pro) with an SH-1 dual needle sensor (1.3 mm in diameter, 30 mm in length, and 6 mm spacing between needles) for rocks (Decagon Device Inc., 2015). For softer rocks, slim drill holes were produced to install the thermal needle. For harder rocks, the needles were placed between two parallel planes (as close as possible) along a pre-existing fracture. The needle was covered with a thermal silver-based gel (99.9% pure silver). For each sample, we obtained ten values recorded at 15 min intervals.

5.6.1.2 Ultrasonic pulse velocity tests of blocks (wave speed)

Tests were conducted on rock blocks following BSI (1986). A V-meter MK IV apparatus was used with a 54 kHz ultrasonic transducer (diameter of 50 mm and length of 81.3 mm), assisted by a lubricant mineral-oil-based gel to increase the contact area between the rock and transducer. In addition to PA and PE tests, we also oriented the transducer in two modes (BSI, 1986): direct (i.e., travel time across the block, DIR) and indirect (i.e., travel time measured between two transducers located on the same side of a block with at least 150 mm of separation, IND). For each test, ten readings were recorded with the two setups.

5.6.1.3 Coring and preparation of samples

The coring process took place outdoors on a wet platform following the suggested method of BSI (2015). A drill bit of 50.8 mm in diameter was used to core samples with an average of 43 mm in diameter. The drilling machine (700 rpm and 3300 W) was held and screwed to a platform floor to reduce vibrations, and the rock samples were stabilized. The water flux was controlled at a minimum rate needed not only to allow for a constant drill advance rate but also to ensure that the samples did not become too wet in order to avoid expansive clay mineral reactions. Note that no dry coring drill bits could be used. The samples were marked to guide the coring, avoiding natural fractures as much as possible. However, this was not always possible, and many samples were broken during drilling and cutting processes, and even after the drying stages, due to the pre-existence of undetected fractures. Challenges in coring associated with swelling clay minerals were faced in marly (B10 and B11) and argillaceous (B7) limestone blocks. These blocks were excluded from further tests. Other blocks of marly limestone (B1, B2, B3, and B9) emitted cracking sounds and presented fractures expanding along planes as a result of water contact.

Cored samples were prepared for mechanical tests in a cutting machine with a diamond cutoff wheel and holders in accordance with ISRM (1978), ISRM (1979) and ASTM (2008). The ends of the cylinders were visually tested to identify any chipped edges, re-passing the surface by the cut-off wheel to ensure the smoothness of the ends. The parallelism of the surface was ensured with the holders of the cutting machine. After cutting, samples were dried in an oven at 105 °C for 24 h (ASTM, 2010) and then naturally cooled to avoid any thermal shock (at 20 °C). In total, 97 cored samples for UCS (21) and BTS (76) were obtained. The slender ratio of length to diameter (L/D) were on average 0.48 for BTS (ranging from 0.39 to 0.60) and 2.2 for UCS (ranging from 1.7 to 2.6). In addition, 34 disc-shaped samples were taken from the cutting leftovers for apparent porosity tests.

5.6.2 Petrophysical Index Tests on Cored Samples

5.6.2.1 Bulk density

Tests were performed in accordance with the ISRM (1977) procedure for the determination of bulk density via the caliper method. A scale with accuracy of ± 0.1 g was used. No tests were conducted in argillaceous limestone as detailed in Section 5.6.1.3.

5.6.2.2 Apparent porosity

Tests were performed in accordance with ASTM (2010) and measured the interconnected void volume. Samples were saturated in tap water for 24 h. The additional weight of water (after

samples were dried with paper towel) was related to the surface connected void volume. To determine the potential swelling impact of samples, the dimensions of the samples were measured before and after the saturation period, as well as it was ensured that samples had no layering or signs of breakings. Tests were conducted only in offcut samples of micritic limestone (i.e., samples that were too short or had no parallel ends). Marly limestone samples were not tested due to their water sensitivity already observed during the coring process. Other lithologies did not provide sufficient samples to conduct the tests.

5.6.2.3 Slake durability index

A slake durability apparatus (A130, Matest) was used with dried samples (ASTM, 2010) submerged in tap water for 2 cycles (Franklin and Chandra, 1972). The retained fragments were weighted after each cycle. The slake durability index was calculated with the weight of the second cycle, and the final shape of the fragment was described and tabulated in APPENDIX A.

5.6.2.4 Wave velocity

Tests were conducted in the direct (i.e., travel time across the sample between two parallel flat sides, DIR) mode for UCS samples of marly and micritic limestone (ISRM, 1978). Ten readings were taken in the same position for each P-wave and S-wave test, and the average value of those ten readings is reported.

5.6.3 Mechanical Strength and Critical Crack Threshold

5.6.3.1 Tensile strength tests

Tensile tests were conducted on two type of PE orientations, performing the tests for the highest tensile strength values according to Dinh et al. (2013) for anisotropic rocks. Both PE1 and PE2 tests are illustrated in Figure 5-3b. No samples of argillaceous limestone were tested, for reasons previously described. The Brazilian test (BTS) method suggested by the ISRM (1978) was used to measure the indirect tensile strength (σ_t) on a CBR-Marshall 50 kN (Figure 5-4a) loading machine with a displacement-controlled rate of 0.003 mm/s so that samples failed at between 30 and 60 s. Samples were placed in a curved hardened steel loading jaw to allocate the applied bearing force. During the BTS tests, 34 of the total 58 PA test results were declared invalid because the samples failed along planes of weakness parallel to the main disc face (i.e., vertical fracture between the two bearing points, as Figure 5-4a shows. The ISRM (1978) states that primary failure (i.e., early peak failure in Figure 5-4a) should be followed by a final failure, with maximum difference of 5%. However, in our tests, this difference was 10% on average, so only 39 out of 76 tests were used to determine the indirect tensile strength.

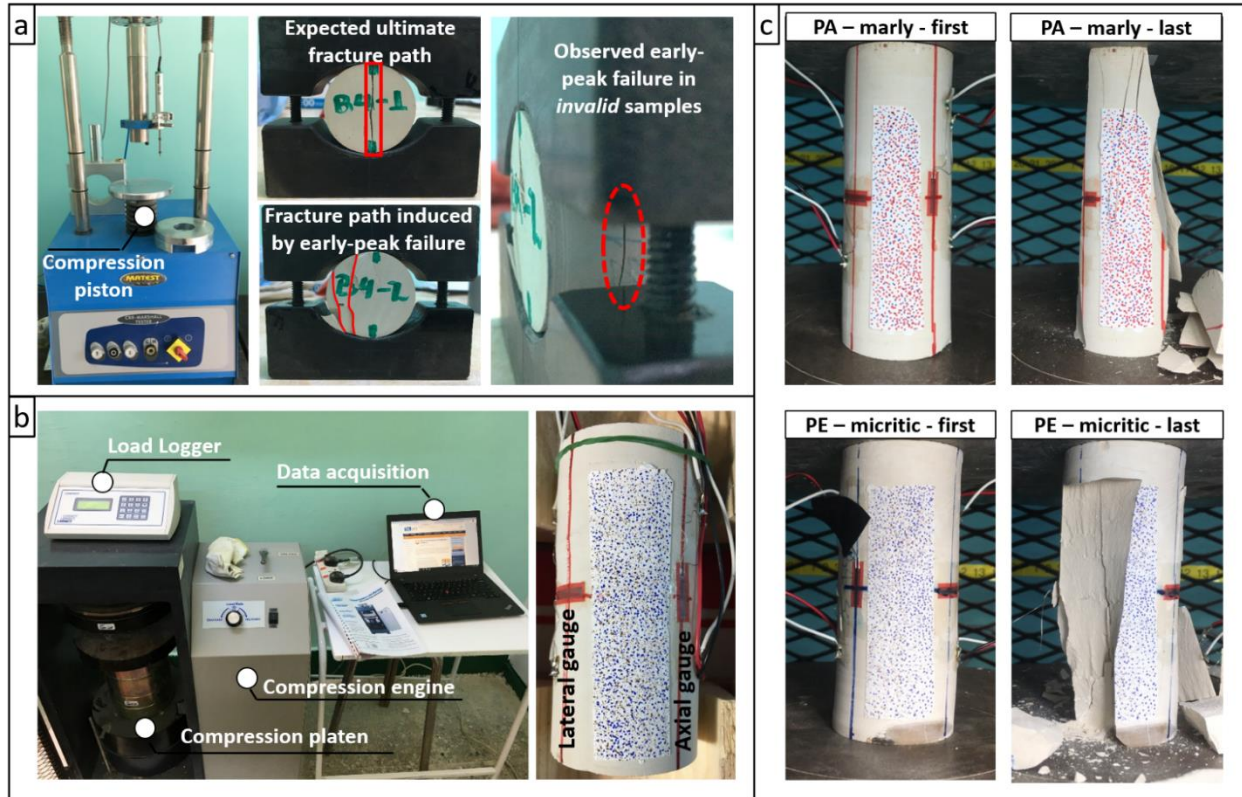


Figure 5-4: Mechanical tests to measure strength of rock samples, with pictures showing the (a) apparatus for BTS tests and curved Brazilian loading jaw with BTS samples shown after peak strength is achieved and the fracture path connecting the two bearing points, and another type of failure influenced by the existence of planes parallel to the disc face (invalid sample). (b) Apparatus and an example specimen used in the UCS test with installed lateral and axial strain gauges on the sample surface, as well as (c) UCS tests of PA and PE samples with pictures of initial state (left) and at peak strength (right).

5.6.3.2 Uniaxial compressive strength (UCS) tests with strain measurements

UCS tests were conducted to determine elastic parameters, critical crack thresholds, and the UCS, in accordance with the ISRM (1979). Strain was measured with strain gauges. The tests were conducted on 16 marly and micritic limestone samples in the PA and PE loading orientations, as shown in Figure 4-3b. In addition, 5 conducted tests recorded the peak strength only (no strain gauges were attached). Sample surfaces were smoothed, and rock dust was removed to ensure that superglue held the contact between the rock surfaces and strain gauges, which were placed on the central region. Axial ($2 \times \epsilon_a$) and lateral ($2 \times \epsilon_l$) average strains were recorded with strain gauges (thermally compensated for steel and with a 10 mm gauge length) at diametrically opposite positions (Figure 4-4b). For the PE samples, gauge locations were selected to avoid chert nodules (less than 15% of sample size), though they were still vertically centered. The strain gauge data were recorded with an HBM strain gauge bridge amplifier (MX1615B). A CT310 compression machine with a maximum load of 2000 kN was used (Figure 4-4b) at a

loading rate of 0.003 mm/s for all tests so that peak strength could be typically reached between 5 and 10 min in accordance with ISRM (1979). Samples were preloaded to 4 kN to ensure that the plates were in full contact with the rock samples before proceeding with the loading and breaking of samples, as shown in Figure 4-4c.

5.6.3.3 Critical crack stress threshold during UCS tests and elastic properties

The critical crack thresholds during UCS tests comprise several stress stages during the loading process of unconfined samples. As introduced by Martin and Chandler (1994), the progression of damage in brittle materials has an initial stress level (i.e., threshold) at which the majority of pre-existing cracks are closed, which is known as crack closure (CC). This is followed by a stress range in which the rock reacts elastically, limited by a second stress threshold called crack initiation (CI). The nonlinear trend in the volumetric strain evolution from this point upwards indicates stress distribution at the grain scale which leads to the formation of new cracks (Brace et al. 1996, Lajtai 1974, Stacey 1981, Diederichs 2007, Ghazvinian 2010, Nicksiar 2013, Perras and Diederichs 2017). When cracks start to interact with each other and coalesce, a new threshold is defined as crack damage (CD). Finally, ultimate failure occurs at peak strength defining the UCS.

To date, no international standard (e.g., ISRM, ASTM, or BS) has published a guideline to determine these stress threshold magnitudes. Here, we employed methodologies derived from the works of Brace et al. (1966), Lajtai (1974), Stacey (1981), Diederichs (2007), and Ghazvinian (2010), which are summarized in Table 4-3. Our CC and CI calculations used the volumetric strain (ϵ_v), mathematically defined as the sum of axial strain (ϵ_a), and two times the lateral strain (ϵ_l) (i.e., mathematically, $\epsilon_v = \epsilon_a + 2 * \epsilon_l$). The CC value was determined to be the average stress given by the methods of Brace et al. (1966) and Lajtai (1974), which rely on determining the point where the stress–strain evolution changes from non-linear (cracks still closing) to linear (most cracks perpendicular to loading are closed). From this point upward on the stress–strain curve, the CI value was defined as the average value amongst all methods from Table 5-3. Note that the CD threshold was not included in this characterization because of the noise in strain data when approaching the peak strength region of the test. The region of the stress–strain curve between CC and CI is known as the elastic region. The average Young’s modulus and Poisson’s ratio were calculated within this elastic region (ISRM, 1979).

Table 5-3: List of techniques for Crack Initiation (CI) determination using strain measurements.

Author	Variables and Method
Brace et al. (1966)	Linearity of volumetric strain and axial stress
Lajtai (1974)	Inflection in trend of lateral strain and axial stress
Stacey (1986)	Linearity of volumetric strain and axial strain
Diederichs (2007)	Maximum point of Poisson's ratio increment and logarithm of axial stress curve
Ghazvinian (2010)	Lateral stiffness increment and axial stress

The elastic properties, the peak strength values and the critical crack stress thresholds are important values for input into numerical models, which can be used to capture past or future rock mass behaviour. This study focused on determining the CI threshold for the Thebes Limestone Formation, not only because these are the first reported values, but also because other studies have indicated the CI threshold is considered a long-term lower bound rock strength value (Diederichs 2007, Damjanac and Fairhurst 2010, Leith et al. 2014). Determining this threshold is critical for understanding the long-term behaviour of the cliffs and tombs in the KV and developing preservation strategies that take this into consideration will be essential given the age of the rock cut cliffs and tombs in the area.

5.7 Geomechanical Behaviour

5.7.1 Overview

We report in Table 5-4, Table 5-5 and Table 5-6 the thermal and geotechnical properties in terms of number of samples; average, maximum, and minimum values; and standard deviation. The results are organized by lithology and test orientation (i.e., PA or PE); the marly and micritic limestone results are shown in Table 5-4, and the argillaceous and silicified limestone results are shown in Table 5-5 and Table 5-6. The data are described in Section 5.7.2. A comparison between these results and published data (Table 5-1) is undertaken in Section 5.7.3 and Section 5.7.4 focuses on the strain measurements during UCS tests and the critical crack thresholds.

Table 5-4: Statistical values of the tested geotechnical parameters for the marly and micritic units. k: thermal conductivity; Sp. Heat: volumetric specific heat; V_{pb}: P-wave velocity measured in rock blocks; I_d: slake durability index of two cycles; γ_b: bulk density; n_{ap}: apparent porosity; V_p: P-wave velocity measured in rock cylinders; V_s: S-wave velocity measured on rock cylinders; σ_t: indirect tensile strength measured via Brazilian test; UCS: uniaxial compressive strength; E: elastic modulus; ν: Poisson's ratio. * Overall values for lithology regardless of parallel (PA) or perpendicular (PE) orientation. ** Measured on UCS samples. Orientation of coring is indicated as PA or PE.

Lithology		k W/mK	Sp. Heat MJ/m ³ K	V _{pb} (DIR) km/s	V _{pb} (IND) km/s	I _d * (%)	n _{ap} * (%)	γ _b * kg/m ³	V _p ** km/s	V _s ** km/s	σ _t MPa	UCS MPa	E GPa	ν
Marly	# Samples	5	5	6	6	5	20	49	3	3	6	3	2	2
	Average	1.08	1.04	1.61	0.75	94	17.4	2022	2.98	1.18	7.4	30.4	18.5	0.29
	Max.	1.30	1.32	3.02	1.26	99	26.2	2247	3.41	1.28	13.2	40.9	21	0.17
	Min.	0.73	0.64	0.45	0.52	85	11.6	1787	2.73	1.10	3.9	22.6	16	0.42
	Std. Dev.	0.19	0.25	0.89	0.2	5.55	4.7	134	0.30	0.07	3.3	7.7		
	# Samples			6	6				4	4	14	4		
	Average			2.49	1.05				2.14	1.17	9.2	39		
	Max.			2.98	2.20				2.40	1.34	15.3	50		
Micritic	Min.			1.80	0.31				1.89	0.96	5.6	27		
	Std. Dev.			0.41	0.6				0.19	0.15	2.6	10.8		
	# Samples	3	3	3	3	3	14	47	5	5	4	3	2	2
	Average	0.70	1.47	2.65	0.73	96	18.2	2062	3.22	1.30	7.7	23.9	19.5	0.20
	Max.	0.86	2.34	3.35	0.92	97	23.9	2926	3.37	1.53	11.4	30.8	22	0.29
	Min.	0.52	1.06	1.14	0.23	96	13.0	1664	3.06	1.08	6.3	20	17	0.10
	Std. Dev.	0.14	0.50	0.78	0.2	0.47	3.4	174	0.12	0.16	2.1	4.9		
	# Samples	2	2	3	3				9	9	8	9	5	5
Perpendicular	Average	0.65	1.62	1.63	0.73				2.20	1.02	7.1	58.3	10.3	0.10
	Max.	0.66	1.87	2.41	0.99				2.46	1.34	8.9	79.9	21.1	0.14
	Min.	0.65	1.36	1.04	0.34				2.05	0.78	5.6	40.9	2.5	0.08
	Std. Dev.			0.48	0.2				0.13	0.18	1.1	12.1	6.4	0.02

Table 5-5: Statistical values of the tested thermal and physical properties of block samples for argillaceous and silicified limestone samples. OR stands for orientation of test loading direction with respect to the bedding planes. The bedding planes were not present in silicified limestone. Statistics were calculated from 10 readings for 1 test conducted for 1 sample of each lithology. k: thermal conductivity; Sp. Heat: volumetric specific heat; V_{pb}: P-wave velocity measured in rock blocks.

Lithology	OR		k W/mK	Sp. Heat MJ/m ³ K	V _{pb} (DIR) km/s	V _{pb} (IND) km/s
Argillaceous	PA	Average	1.08	1.06	2.55	1.30
		Max.	1.08	1.06	2.64	1.31
		Min.	1.07	1.06	2.46	1.29
		Std. Dev.	0.00		0.08	0.01
	PE	Average	1.04	1.07	1.19	0.73
		Max.	1.05	1.08	1.23	0.85
		Min.	1.02	1.06	1.08	0.64
		Std. Dev.	0.01	0.01	0.05	0.1
Silicified		Average	1.44	1.90	1.18	0.50
		Max.	1.51	2.03	1.3	0.50
		Min.	1.41	1.82	1.1	0.49
		Std. Dev.	0.02	0.08	0.06	0.01

Table 5-6: Statistical values of the tested physical and peak strength properties of five disc samples from the silicified limestone unit. Bedding planes were not observed in silicified samples (massive). γ_b: bulk density; σ_t: indirect tensile strength measured via Brazilian test.

Lithology		γ _b kg/m ³	σ _t MPa
Silicified	Average	2550	20.3
	Max.	2571	29.7
	Min.	2531	14.7
	Std. Dev.	18	6.8

5.7.2 Standard Geotechnical Properties

Standard geotechnical tests were conducted on block and cored samples. The average and coefficient of variation (CV) were used to investigate the variability of the test results within each test type and lithology.

5.7.2.1 Thermal conductivity and volumetric specific heat

The results for thermal properties are plotted in Figure 5-5a,b for Thermal Conductivity (k) and Volumetric Specific Heat (Sp). Thermal properties for the silicified and marly limestone samples were measured within existing fractures. The silicified limestone had the highest average value for k (1.44 W/mK), whereas the marly limestone had the second highest average value (1.08 W/mK; CV: 0.1) for PA tests. However, block B10 of the marly limestone had the lowest k (0.76 W/mK) of all blocks, which lowered the reported average k value for this lithology (Table 5-4). The argillaceous limestone had a range of average values from 1.04 to 1.08 W/mK, with PA values being the highest. The micritic limestone had the lowest average value (PA: 0.70 W/mK; PE: 0.65 W/mK). The highest k value for micritic limestone in the PA test was for B6 (0.84 W/mK), in contrast to the B4 and B5 blocks (0.56 W/mK). For the micritic limestone PE tests, only B4 and B5 were tested. The Specific Heat results showed that silicified limestone had the highest average value (1.90 MJ/m³K), and the marly limestone had the lowest values (1.04 MJ/m³K), with a wide variability between blocks (CV: 0.25). For the micritic limestone PA tests, the B6 sample had the lowest values (1.1 MJ/m³K) in comparison to block B4 (2.3 MJ/m³K) and B5 (1.47 MJ/m³K) samples. The argillaceous limestone had a lower than 1% difference between the PA and PE tests, with an average of 1.06 MJ/m³K.

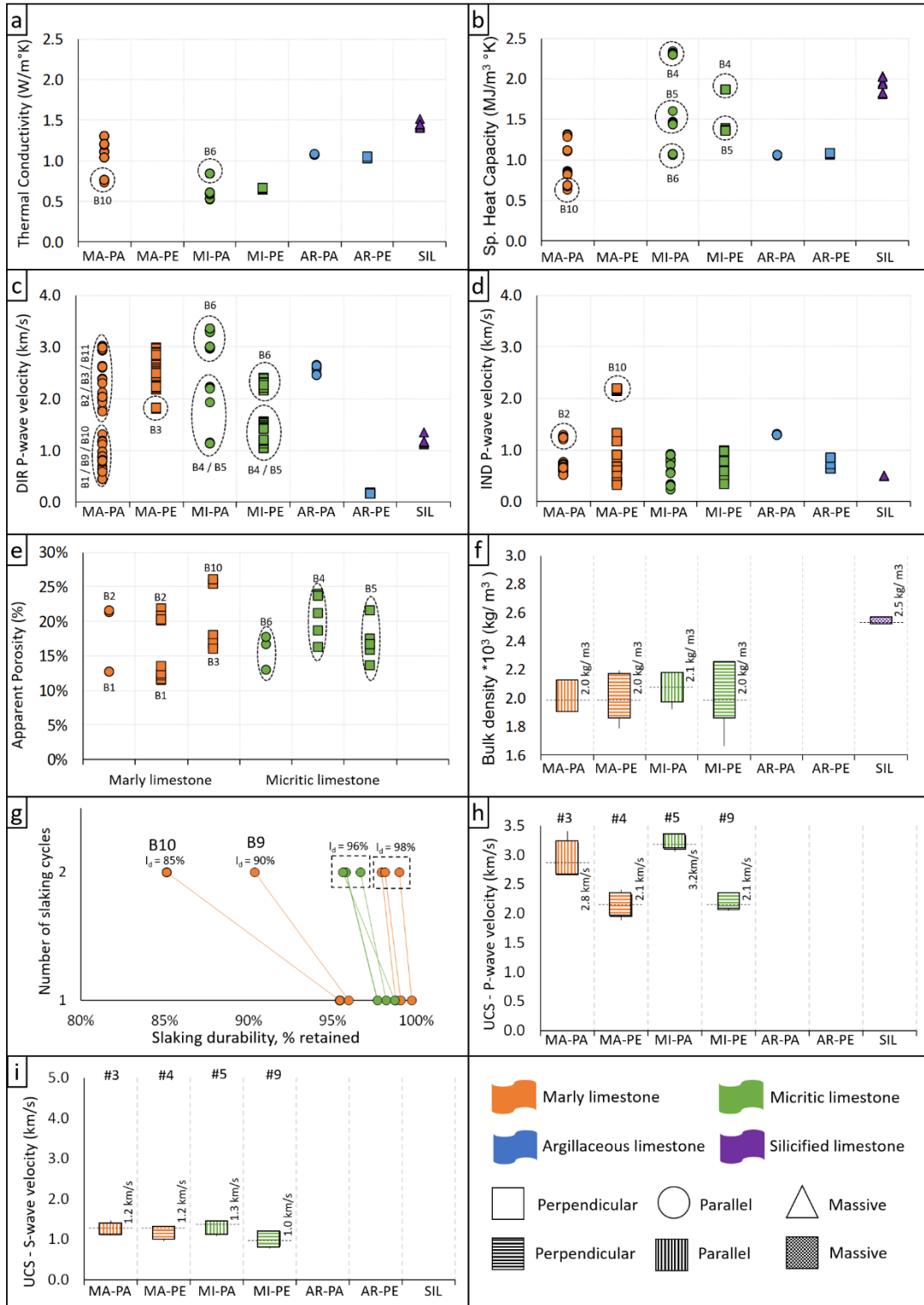


Figure 5-5: Test results for block samples characterized by lithology and test orientation. The results for (a) thermal conductivity; (b) specific heat capacity; (c) P-wave velocity in the direct (DIR) technique; (d) P-wave velocity in the indirect (IND) technique; (e) apparent porosity; (f) bulk density; (g) slake durability index for the second cycle; (h) P-wave velocity measured in UCS samples; and (i) S-wave velocity measured on UCS samples are shown. MA: marly limestone; MI: micritic limestone; AR: argillaceous limestone; SIL: silicified limestone; PA: parallel; PE: perpendicular.

5.7.2.2 P-wave velocity measured and indirect methods in blocks

As stated in Section 5.6.1.2, the definitions of the direct (DIR, travel time across the block) and indirect (IND, travel time measured between two transducers located at the same block side) methods are based on BSI (1986). The tests conducted in the DIR mode had a higher wave speed (2.06 km/s) than those in the IND mode (0.85 km/s), which was consistent across the different tested lithologies. Regarding the DIR tests (Figure 5-5c), the marly limestone blocks had a wider variability for PA tests (CV: 0.27) than PE tests (CV: 0.16). Block samples for the PA tests seemed to be clustered, e.g., B1, B9, and B10 (0.8 km/s; CV: 0.3) and B2, B3, and B11 (2.4 km/s; CV: 0.2). For the PE tests of the marly limestone samples, B3 had the lowest wave speed (1.8 km/s) in comparison to other blocks (2.6 km/s). The tests for micritic limestone showed higher values for B6 (PE: 2.3 km/s; PA: 3.3 km/s) than for B4 and B5 (PE: 1.3 km/s; PA: 2.3 km/s). The argillaceous limestone block had a difference of 1.3 km/s between PA (2.5 km/s) and PE (1.2 km/s). Regarding the IND mode (Figure 4-5d), the marly limestone blocks B2 (1.2 km/s) and B10 (2.17 km/s) had the highest wave speed for PA and PE, respectively. Similarly, the average results were higher for PE (1.05 km/s) than PA (0.75 km/s). The micritic limestone tests in the PA and PE orientations had a similar wave speed of 0.73 km/s, whereas the argillaceous limestone block had a greater wave speed for PA (1.3 km/s) than PE (0.7 km/s).

5.7.2.3 Apparent porosity

The Apparent Porosity (n_{ap}) tests results showed no difference between the PA and PE orientations (Figure 5-5e). The micritic limestone had an average of 23.9%, with 5% difference in results between blocks, with the variabilities within B4 (CV:0.14), B5 (CV:0.1), and B6 (CV:0.05) smaller than the marly limestone data.

5.7.2.4 Bulk density

The Bulk Density (γ_b) was measured for UCS and BTS samples. The results are plotted in Figure 5-5f. All rock units had little variability in their results (CV < 0.1). The silicified limestone had the largest bulk density (2550 kg/m³), as measured in five BTS samples. The marly limestone (2020 kg/m³) and micritic limestone (2060 kg/m³) yielded distinct smaller average values compared to the silicified limestone.

5.7.2.5 Slake durability index

We expressed the results of the Slake Durability Index (I_d) in the percentage of retained material within the steel drums after two cycles, as shown in Figure 5-5g, and we classified the slaking durability according to the work of Franklin and Chandra (1972). Here, the marly limestone blocks

had two groups of slaking durability, with average I_d results ranking from Extremely High ($I_d = 98\%$ for B1, B2, and B3) to High ($I_d = 87\%$ for B9 and B10). The micritic limestone had an Extremely High ($I_d = 96\%$) durability, with closely grouped results. A description of retained fragments is provided in APPENDIX A.

5.7.2.6 Wave velocity of cored samples

Both P-wave (V_p) and S-wave (V_s) velocities were 30% higher in the PA orientation than in the PE orientation for both marly and micritic limestone. The results by lithology are plotted in Figure 5-5h,i. For V_p tests, the micritic limestone (PA: 3.22 km/s; PE: 2.20 km/s) had a higher average speed than marly limestone (PA: 2.98 km/s; PE: 2.14 km/s). Smaller differences between PA and PE were measured on average for V_s of micritic limestone (PA: 1.30 km/s; PE: 1.02 km/s) and marly limestone (PA: 1.18 km/s; PE: 1.17 km/s).

5.7.2.7 Indirect tensile strength

All indirect tensile strength (σ_t) data are plotted in Figure 5-6a versus loading rate. Invalid tests are included to show how the primary failure was systematically observed along different ranges of stresses. A summary of valid tests is plotted in Figure 5-6b. Because the loading machine was capable of controlling the displacement rate in mm/s, different loading rates in kN/s resulted in accordance with the stiffness of each rock type. The silicified limestone had the highest loading rate (0.28 kN/s) and σ_t of on average 20.3 MPa. The marly limestone required a higher loading rate (0.21 kN/s) than the micritic limestone (0.17 kN/s) in both PE1 and PA2 test orientations. For the micritic limestone, the PE1 tests (7.7 MPa) had slightly higher values than the PE2 tests (7.1 MPa). This relates to one BTS sample from B6 that had a σ_t of 11.4 MPa in PE1 direction, whilst the other PE1 samples (three samples from B5) had an average value of 6.3 MPa. The marly limestone had higher values for the PE2 tests (9.1 MPa) than the PE1 tests (7.4 MPa).

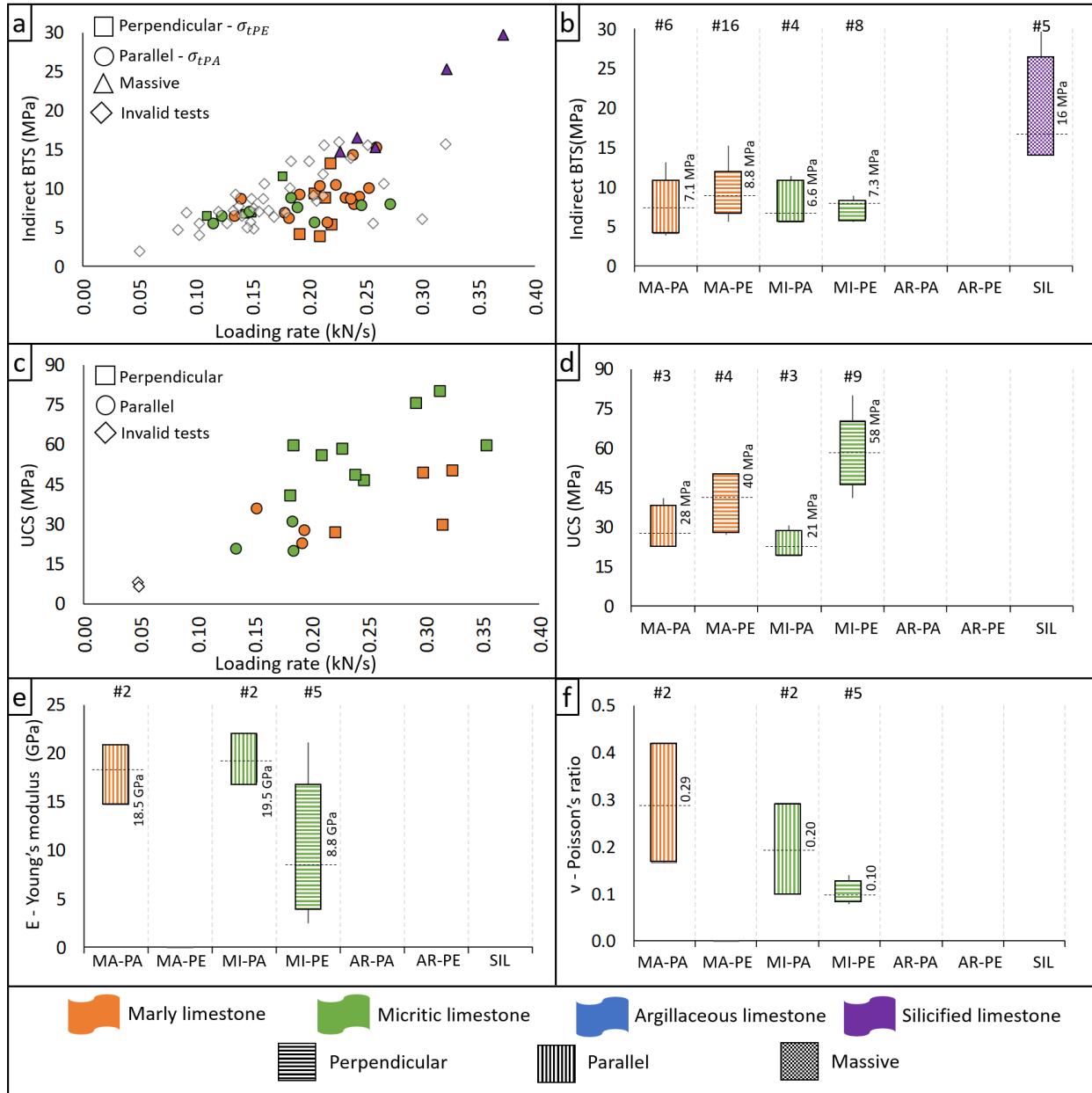


Figure 5-6: Mechanical results for BTS and UCS tests, with the number of samples indicated in individual graphs on top of each data group. Middle bars of the box plot and the associated values on the plots show the median value. (a) loading rate of BTS tests and strength; (b) indirect tensile strength results; (c) loading rate of UCS tests and strength; as well as for each rock unit and orientation, the (d) UCS results; (e) Young's modulus; and (f) Poisson's ratio. MA: marly limestone; MI: micritic limestone; AR: argillaceous limestone; SIL: silicified limestone; PA: parallel; PE: perpendicular.

5.7.2.8 Unconfined compression tests, Young's modulus and Poisson's ratio

The Unconfined compressive strength (UCS) was conducted with an apparatus set to a loading rate of 0.003 mm/s that, based on the stiffness of each rock type, resulted in different loading rates in kN/s. The UCS tests in PE had a higher loading rate (0.26 kN/s) than in PA (0.14 kN/s). This difference was consistent across the different tested lithologies. Two

samples of micritic limestone were discarded since they broke at low loading rates (Figure 5-6c). Therefore, 19 out of 21 tests were used to determine the UCS value, as summarized in Figure 5-6d. In general, the micritic limestone had a higher UCS (50 MPa) than the marly limestone (35 MPa), for both PA and PE orientations. The highest difference was seen in the PE tests, in which micritic limestone showed on average 58 MPa and the marly limestone had on average 39 MPa. Elastic properties of Young's modulus (E) and Poisson's ratio (ν) could not be determined for all UCS samples because strains could not always be accurately measured (i.e., no strain gauges or noisy strain signals during tests). Hence, only values from eight samples of micritic limestone (two PA and six PE) and two PA samples of marly limestone can be reported. The results are plotted in Figure 5-6e,f. The micritic limestone had higher average elastic parameters for PA tests (E : 19.5 GPa; ν : 0.2) than PE tests (E : 10 GPa; ν : 0.1). The marly limestone had the highest ν in PA (0.3) amongst all tests.

5.7.3 Comparison of Geotechnical Properties with Existing Data

5.7.3.1 Analysis of thermal conductivity and specific heat results

No thermal properties for Member I, Thebes Limestone Formation, were publicly available at the time of this work, so the analysis focuses on limestone rocks from other locations. Physical features such as porosity and density are useful indicators for estimating the degree of compaction of rocks, which is linked to thermal conductivity (Robertson, 1958). For instance, Çanakci et al. (2007) tested limestone from Southeast Turkey and found an exponential direct correlation between density and thermal conductivity (k), with a range of k values from 0.8 W/mK to 2.5 W/mK for a range of densities from 1800 kg/m³ to 2400 kg/m³. We observed a range of density from 2000 kg/m³ to 2700 kg/m³ and a range of k from 0.7 W/mK to 1.4 W/mK. Similarly, Robertson (1958) reviewed literature values of k for limestone and gathered a database that features a range from 1 W/mK to 2 W/mK and porosity values from 20% to 75%. Our tested samples had an apparent porosity ranging between 13% and 26%, designating the tested samples in the lower band of Robertson's reported values for k lower than 1 W/mK.

Specific heat is defined as the product between rock bulk density and heat capacity. The values of the heat capacity of rocks are influenced by the mineralogical composition of the rock and the individual heat capacity of its constitutive minerals (Kappelmeyer and Haenel, 1974). Here, the silicified limestone block showed the highest specific heat and density, resulting in the greatest heat capacity of 0.75 kJ/kgK. The heat capacity ranged from 0.5 kJ/kgK to 0.65 kJ/kgK for the marly, micritic, and argillaceous limestones. The literature values of heat capacity for marly and

micritic limestones were reported by Kappelmeyer and Haenel (1974) as 0.9 kJ/kgK, by Robertson (1988) from 0.83 kJ/kgK to 1 kJ/kgK, and by Homuth et al. (2015) from 0.6 kJ/kgK to 1.0 kJ/kgK at 20 °C in dry conditions. The differences in values can be attributed to the depth of penetration of the sensors, the degree of weathering of the surfaces, and the amount of clay minerals. It is worth noting that thermal conductivity can almost linearly decrease with temperature in regions below 100 °C (Robertson, 1988). This variation could be neglected in our work since we measured thermal properties in a range of temperature between 15 °C and 20 °C.

5.7.3.2 Analysis of P-wave speed in blocks

The P-wave speed in blocks (V_{pb}) results were higher in the PA than PE orientations for most samples. However, the marly limestone V_{pb} was lower in the PA orientation than the PE orientation, likely because of the existence of closely spaced discontinuities oriented 45° to 90° from bedding planes that reduced the V_{pb} values for PA (rock discontinuities in Table 5-2). It was expected that samples had a higher V_{pb} for the DIR compared to IND tests because of the poorer integrity of the shallow layers of the blocks in contrast to the block's cores (i.e., blocks were not sampled from fresh rock walls). Likewise, Maissen (2019) reported higher values of V_{pb} in the DIR mode of different samples of marly limestone in the KV for PE (2.95 km/s; CV: 0.17) and PA (3.15 km/s; CV: 0.06). However, Maissen (2019) did not report the fracture state of the rock samples to discuss whether the differences were related to the integrity of the samples.

5.7.3.3 Analysis of apparent porosity

The Apparent Porosity (n_{ap}) of marly limestone from KV5 was previously presented by Hemeda (2018), with values ranging from 14% to 19%, though the author did not refer to a procedure for the calculation. Similarly, Lazar (1995) reported values for porosity ranging from 1.1% to 27.5% for 13 samples of marlstone, with an average of 13%. Wüst (1995) determined an average of 19.7% for the porosity of eight samples of marl and limestone, with values ranging from 14% to 34.7%. Wüst and Schlüchter (2000) examined six samples from KV17 (marlstone and shale), with n_{ap} ranging from 15% to 23% (average of 18%). However, none of the authors detailed how they dealt with the water sensitivity of the samples during testing. Based on published data, the results from this research fall within a known range of values, with an average of 18.2% for micritic limestone.

5.7.3.4 Analysis of bulk density

For the Bulk Density (γ_b), at the Theban Necropolis, Lazar (1995) provided information for 13 samples of chalk and marl, with an average value of 2280 kg/m³ ranging from 1950 kg/m³ to 2650 kg/m³. Wüst (1995) also indicated a mean value of 2100 kg/m³, with a range of values

from 1710 kg/m³ to 2210 kg/m³, tested on eight samples from Wadi Qabbanat el-Gouroud (Figure 4-1, 2.5 km south of the KV). Wüst and Schlüchter (2000) provided density values for six marlstone samples from the KV, with an average value of 2150 kg/m³ (range from 2050 kg/m³ to 2180 kg/m³). Hemeda (2018) reported unit weight values of marly limestone for samples from KV5 (unknown number of samples), which ranged from 20 kN/m³ to 21 kN/m³ (i.e., from 2039 kg/m³ to 2141 kg/m³). The results for the marly and micritic limestone altogether ranged from 1650 kg/m³ to 2250 kg/m³, so our results fall within published ranges. For silicified limestone from the KV no values were reported in the literature. However, Manger (1963) gave values of density for “hard and dense” Eocene limestone ranging from 2300 kg/m³ to 2700 kg/m³ that had a porosity of around 2% and could be linked to the silicified limestone samples. This provides an upper boundary for the density of silicified limestone, and our results fall within the range.

5.7.3.5 Analysis of slake durability index

There were no previous slake durability index (I_d) data from the KV by the time this research was conducted. The marly limestone blocks B9 and B10 (both from the excavation material of KV17) had a lower I_d (87%—High) than other blocks of the same lithology (B1, B2, and B3: 98%—Extremely High), likely related to past flooding events (i.e., natural slaking) since the blocks originating from debris. According to Miscevic and Vlastelica (2011), an additional slaking cycle (followed by a drying stage) could reduce the I_d by 5% to 10%. The retained fragments after the second cycle, for B9 and B10, were similar to small loose material in angular shape, with larger pieces with cracks on the surface, which differed from the more packed integrity of retained fragments of B1, B2, and B3 (APPENDIX A). Marly limestone has been found to have a high to very high durability in regions of the Middle East (Khalily et al. 2013, Azimian and Ajalloeian 2015, Cicek et al. 2016). Arman et al. (2016) also reported a slake durability index value for “soft limestone” (i.e., micritic texture from United Arab Emirates) of about 97%, which aligns with the micritic limestone values from our research.

5.7.3.6 Analysis of wave velocity of cored samples

The tests conducted in the PA orientation had wave speeds 40% faster than those conducted in the PE orientation. This difference was consistent across the tested lithologies and similar to what was observed for block samples and bedding plane orientations (see Section 5.7.2.2). Comparatively, most cored UCS samples had higher wave speeds than those measured in the blocks themselves by about 25%. This could be explained by weathered rims of blocks, fractures and the presence of silica bands in blocks, which were avoided as much as possible during the coring process. From the literature, Lazar (1995) reported values from P-wave

speed tests in marly and micritic limestone from Wadi el-Machtar (Figure 5-1, 2.5 km east of the KV). The tests in the PA orientation (three samples) yielded an average value of 3.32 km/s, ranging from 3.28 km/s to 3.39 km/s, whilst the tests in the PE orientation (three samples) gave on average 2.36 km/s with a range from 2.15 km/s to 2.70 km/s. The results of Lazar (1995) were about 0.2 km/s higher than the results of this research, although they state that three unweathered, oriented samples of Member I were taken and having only three samples may have influence the results. A similar coring integrity was targeted in our research (i.e., unweathered). The integrity of the sample (i.e., unaltered cored samples) facilitated the travel of the ultrasonic wave by avoiding weathered areas that would slow the wave down. With more test results in this study, as well as considering the natural variability of geo-materials, small differences from other studies are expected. There was no reported value for S-wave speed in the literature.

5.7.3.7 Analysis of indirect tensile strength (Brazilian test results)

Limited information of tensile strength (σ_t) on aspects such as rock formation, sample integrity, fracturing, and weathering degree was provided in the literature. These parameters must be considered when comparing test results, so the validation of the reported values of this research relied on the procedure suggested by the ISRM (1978) under the inherent properties of the samples (other physical properties and rock unit characterization). It is worth to point out that our samples were tested under the maximum tensile stress capable of withstand in two orientations according to Dihn et al. (2013), therefore it might be expected that values from other authors could be lower than the ones from our tests. Furthermore, at the KV, literature values are limited to selected places and few samples. For instance, Aydan et al. (2018) mentioned a range from 4.4 to 5.1 MPa for “soft limestone” tested in the tomb 22 at the West Valley (WV22), with no information regarding the number of samples or the mean value. These values were lower than the results presented here for the marly and micritic limestone together, which ranged from 3.9 MPa to 15.3 MPa. Similarly, Dziedzic and Michiewicz (2018) reported values of strength in tension for limestone blocks from the temple of Hatshepsut, quarried about 3500 years ago at 3 km north of el-Qurna hill. The tests were conducted as bending tests on beams sampled from the temple, resulting in strength values ranging from 2.7 MPa to 3.4 MPa and an average value of 3 MPa.

Other researchers have conducted analyses of tensile strength at other locations in Egypt, though far from the Theban Necropolis. Ali and Yang (2014) tested marly limestone samples (Palaeocene) collected in Qena (Egypt), and they reported an average value of 5.3 MPa for dense samples (porosity of 7.6% and density of 2450 kg/m³). These results were complemented by Ali

and Ahmed (2019), who tested the same rock type in the PE orientation to report tensile strength values with an average of 5.5 MPa and a range from 3.9 to 7.7 MPa. Further north in Cairo, Abdelrahman et al. (2019) tested limestone from different quarries around the Cairo metropolitan area; the authors found tensile strengths of 1.9, 2, and 2.5 MPa of three dense samples with porosities of 2.7%, 2.9%, and 2.86%, respectively, together with an average density of 2600 kg/m³.

5.7.3.8 Analysis of unconfined compressive strength

The unconfined compressive strength (UCS) for Thebes Limestone Formation was previously published by Lazar (1995), for marly limestone collected from Wadi el-Machtar (Figure 5-1). The marly limestone average results from Lazar (1995) were 35 MPa (ranging from 16 MPa to 47.7 MPa) and 55 MPa (ranging from 22 MPa to 72 MPa) for tests measured in the PA and PE orientations, respectively. Our average UCS results for the marly limestone measured in the PA and PE orientations were 22.6 MPa and 39 MPa, respectively, which is lower than Lazar's average results. However, our average measured PE to PA ratio for the marly limestone of 1.7 was similar to 1.6 reported by Lazar (1995). For the micritic limestone from our tests, this ratio was 2.4 (PA: 23.8 MPa; PE: 58 MPa).

It is worth mentioning that the variability in published results for the marly limestone is quite wide. For instance, a UCS of 78.2 MPa was reported by Wüst and McLane (2000) for one sample of marly limestone from KV17, whereas Hemeda (2021) reported a range of values from 8 MPa to 9.3 MPa for seven samples from the interior of tomb KV57. Hemeda (2018) reported UCS values for samples from the interior of tomb KV5 as "sidewalls are between 6 MPa and 7 MPa, while the strength of the supporting rock pillar is 1 MPa because of the impact of the past and recent flash floods", possibly measured in the PA orientation because of the exposure of the bedding planes in the tombs' walls (i.e., running subparallel to the floor of tunnels and caverns), although the method of measurement was not reported. This could be a good indicator of how prone the marly limestone is to losing strength due to variations in weathering degree (i.e., water contact, for instance). Limited information from similar rock types in other locations across Egypt was available, particularly regarding anisotropy and tests clearly documenting PA and/or PE orientations. For example, UCS tests carried out on marly limestone samples collected at Qena, Egypt, resulted in an average of 74 MPa for dense samples with a porosity of 7.6% and a density of 2450 kg/m³, but the authors did not indicate the orientation of the load and bedding planes (Ali and Ahmed, 2019). Ali and Ahmed (2019) also tested ten samples of marly limestone from Qena, and the reported value of the UCS measured in the PE orientation was 74 MPa, with a range from 54 MPa to 96 MPa. Additionally, Arnold (1991) reviewed the

properties of Egyptian building stone across Egypt, limiting the type of limestone in an engineering manner based on sample density (from 1700 kg/m³ to 2600 kg/m³), assigning a wide range of UCS values, from 20 to 80 MPa, to porous limestone. The range of values published by Arnold (1991) for both density and UCS were similar to the measured properties in this research.

5.7.3.9 Analysis of Young's modulus and Poisson's ratio

The average results for Young's modulus (E) in the present study were higher in the PA (19.5 GPa) than PE orientations (10.3 GPa) for the micritic limestone. Maissen (2019) estimated values of 8.2 and 7.3 GPa for block samples measured in the PE and PA orientations, respectively. The author conducted P-wave velocity tests on block samples of marly limestone from the KV and used empirical relationships to determine (Maissen, 2019). These values indicated a slight anisotropy in the elasticity of the rock and substantially lower E for PA samples. Hemeda (2018) reported a single value of 10 GPa for the elastic modulus of marly limestone samples from KV5, and Aydan et al. (2018) indicated a range from 2 GPa to 10 GPa for "soft limestone" from a WV22 tomb. None of the other researchers provided information regarding the number of samples, orientation with respect to the bedding planes, or the type of test method for the modulus.

We found average Poisson's ratios (ν) of 0.2 (PA) and 0.1 (PE) for the micritic limestone. Gercek (2007) collected data from several publications to determine a range for limestone from 0.10 to 0.32. The author also discussed the anisotropy (i.e., the transverse isotropy) of other sedimentary rocks (sandstone, claystone, and siltstone) measured with static methods, showing that the ratio between highest and lowest ν for the same sample could vary from 1.2 to 2.3. The micritic limestone from the present study had a ratio of 2, which falls within the reported limits by Gercek (2007). However, this is just a referential comparison because Gercek's data (Gercek, 2017) did not cover the specific tested lithology in the present study. For the marly limestone samples, the literature values did not help in determining an actual range of elastic parameter values because of the lack of testing information. For instance, Abdallah and Helal (1990) used a value of 0.21 for limestone samples collected from the Hatshepsut temple, whereas Hemeda (2021) reported a range from 0.25 to 0.30 for samples from KV57.

5.7.4 Analysis of Strain Measurements and Critical Crack Threshold

5.7.4.1 Maximum deformation at the peak strength

The samples that were gauged and not used, had signal noise problems near or above CD that resulted in sudden changes in trends (e.g., unforeseen spikes or null values), likely a result of damage to the gauges during sample fracturing and this interfered with the strain characterization (i.e., to calculate ϵ_a and ϵ_l). Therefore, 9 out of 16 samples that were measured with strain gauges could be analyzed. The resulting stress–strain curves of the marly and micritic limestone are displayed in Figure 5-7a,b for PA and PE, respectively. The axial strains measured in the PE orientation reached up to six times greater values than those measured in PA (on average PE: 0.78%; PA: 0.13%). For the micritic limestone, the PE tests (5 samples) resulted in axial strains ranging from 0.55% to 1.28%, whereas the PA tests (2 samples) resulted in lower strain values from 0.11% and 0.14%. These differences between PA and PE values for axial deformations can be explained by the orientation of bedding planes with respect to loading direction and failure planes. For instance, in the PA samples, the bedding planes tended to bend, and the strain gauges therefore measured shorter axial deformations. On the other hand, in the PE samples bedding planes compress before failure, which resulted in larger deformations.

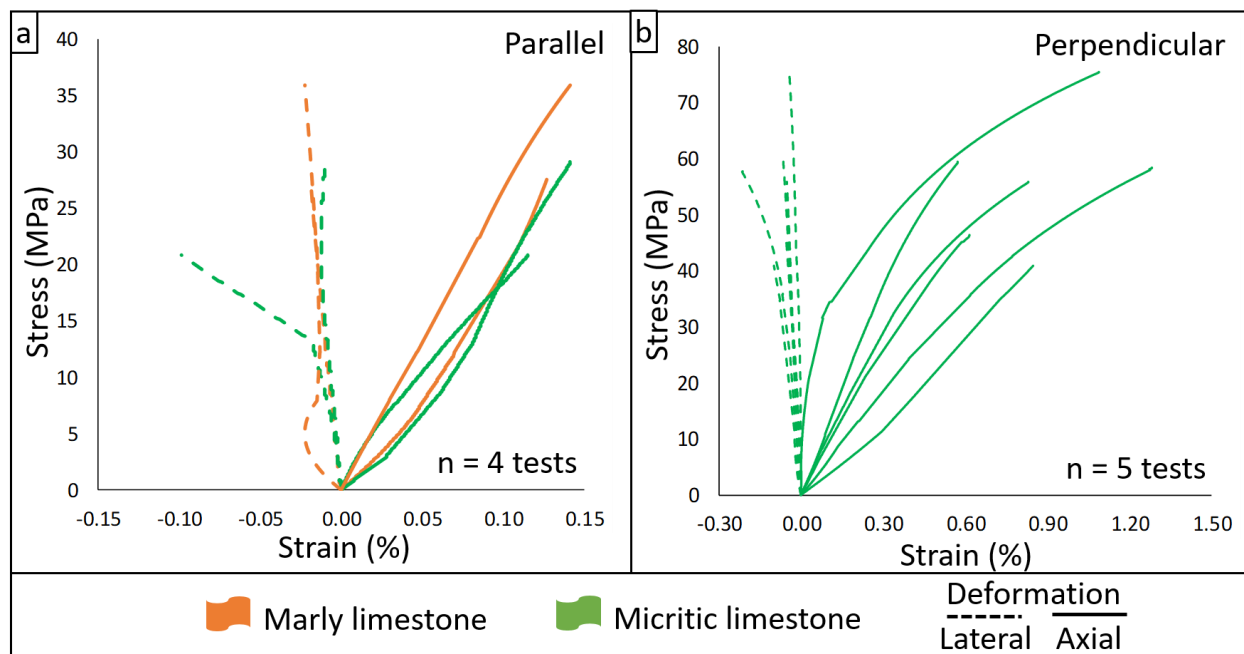


Figure 5-7: Stress–strain curve for UCS tests with strain measurements. Samples are grouped by lithology and orientation of bedding planes. Samples with silica bands are not plotted in the graph (see Section 4.7.3), with (a) the stress–strain curves for PA samples and (b) the stress–strain curves for PE samples. The solid line shows the axial deformations, and the dashed line shows the lateral deformations.

Literature values for UCS with strain measurements in cylindrical samples from the KV are limited to Wüst and McLane (2000), who measured the axial strain of a marlstone sample from Member I, collected from KV17. The sample was tested in PE, reporting a maximum strain of 0.4% at 78.2 MPa. However, their sample was 50.8 mm in diameter and had a length to diameter ratio (L/D) of 1.26; in contrast, our samples had an average diameter of 43 mm and L/D ratio of 2.43. This may have contributed to a comparatively lower strain. Note that the ISRM (1979) suggests a minimum L/D of 2.

5.7.4.2 Critical crack stress threshold from UCS tests

The critical crack thresholds were only characterized in terms of CC and CI because these are essential thresholds that can aid in understanding cracking process and of particular interest the long-term lower bound strength as previously mentioned. In addition, the strain measurements became unreliable due to gauge failure in the region where CD was expected. The results are listed in Table 5-7. For the CC threshold, the micritic limestone tests conducted in the PA orientation (6.9 MPa) had lower average stress magnitude than those in the PE orientation (12.5 MPa), which was consistent with the UCS value (PA: 25.8 MPa; PE: 56.1 MPa). Thus, when comparing the results in terms of stress magnitude as the ratio of CC to UCS, the PA tests (two samples) and PE tests (five samples) had averages of 0.27 and 0.22, respectively. Similar results were obtained for PA tests in marly limestone, with an average of 0.25. This means that PA-oriented tests had to reach proportionally higher thresholds of stress to achieve the closure of their existing cracks. The average ratio of CI to UCS for the micritic limestone was 0.42 for the PE orientation (ranging from 0.40 to 0.44) and 0.45 for the PA orientation (two samples only: 0.47 and 0.42 each). The marly limestone results (two samples) yielded a ratio of 0.4.

Table 5-7: Summary of Uniaxial Compressive Strength (UCS), crack closure stress (CC) and crack initiation stress (CI) levels, for marly and micritic limestone from Member I, Thebes Limestone Formation. Brackets indicate the thresholds in ratio of stress to UCS. Samples with silica bands were excluded here and average UCS of the remaining tests are given. # stands for number.

Rock Type		Marly Limestone		Micritic Limestone	
Coring Orientation		PA	PE	PA	PE
# Samples		2		2	5
UCS MPa *	Average	34.3		25.8	56.1
	Average	7.3		6.9	12.5
	Max.	7.7		5.6	20.0
	Min.	7.0		8.3	6.3
CC **	Std. Dev.				4.7
	Average	14.1		11.4	23.8
	Max.	16.8		13.1	33.0
	Min.	11.4		9.7	16.2
CI ***	Std. Dev.				5.6

The results of different CI calculation methods are plotted in Figure 5-8. Even though the average value given by all five methods was summarized for this research in Table 5-3, one can identify distinct differences in CI values calculated by each method related to the different principles and numerical inputs associated with each method. Overall, for the micritic limestone measured in the PE orientation using the method proposed by Ghazvinian (2010) set a general lower bound (0.39), whereas the methods of Lajtai (1974) and Brace (1966) defined an upper boundary (0.45). Values closer to the average CI value (0.41) were calculated by the methods of Stacey (1981) and Diederichs (2007). Brace (1966), Lajtai (1974) and Ghazvinian (2010) did not use the correlation between deformations; they focused on deformations against stress, which could be useful for isotropic materials. Nevertheless, Brace (1966) and Lajtai (1974) use the lateral strain to seek the CI stress value, which would tend to be overestimated because of the failing mechanism of bedding planes. In fact, Ghazvinian (2010) method based on both ε_a and ε_l could diminish the bias given by the orientation of the test and the strain gauges with respect to the bedding planes. Stacey (1981) and Diederichs (2007) correlated variations in lateral and axial strains that concern the presence of bedding planes in intact rock. For the PA tests on both marly and micritic limestone, the upper and lower boundaries are not consistent based on any given method. It is worth noting that the PA-oriented tests were highly dependent on the ε_l magnitude because the strain gauges were placed across the bedding planes and the ε_l measured was therefore at the highest possible lateral deformation, as opposed to having the gauges in the bedding plane itself. Accordingly, we applied the method of Diederichs (2007), who used increments in Poisson's ratio (i.e., capturing the bulk deformation of the sample) against the stress increments, which resulted in the most centered values.

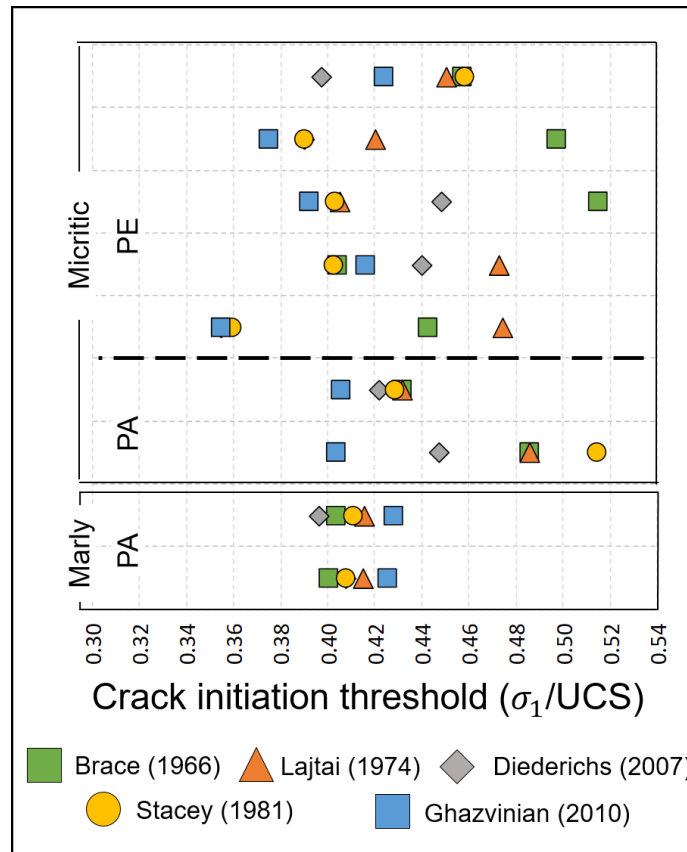


Figure 5-8: The crack initiation (CI) threshold values were calculated after several techniques detailed in Table 5-3. Legend stands for different calculation methods from Brace et al. (1966), Lajtai (1974), Stacey (1981), Diederichs (2007), and Ghazvinian (2010). The marly and micritic limestone results are shown separately, distinguishing between PA and PE for the micritic limestone. No samples of PE for marly limestone could be used to calculate the CI threshold. PA: parallel; PE perpendicular.

5.7.4.3 Comparison of crack initiation stress threshold to literature values

Most authors have found that the CI threshold falls within a wide band ranging from 0.3 to 0.6 of the ratio CI stress to UCS, regardless of the petrophysical properties of the rocks. For sedimentary rocks, Wen et al. (2018) tested a group of samples and determined that the ratio of CI to UCS had an average value between 0.45 and 0.65. Meyer (2018) studied CI threshold using acoustic emission (AE) analysis and samples of Indiana and Cobourg Limestone, with average results from 0.45 to 0.55. Peng et al. (2018) also conducted tests of four different types of limestone from the United States (Indiana Limestone), France (oolithic Malm Limestone), and Israel (Bina Limestone and Nekarot Limestone), reporting an average ratio of CI to UCS of 0.4 (ranging from 0.32 to 0.48). Similarly, Pepe et al. (2018) tested sedimentary rocks (limestone with a quartz-calcite-muscovite matrix) and reported a ratio of CI to UCS of 0.49 (ranging from 0.41 to 0.57). Conversely, Ündül et al. (2016) reported in biomicritic and nodular limestone with bedding planes, with a CI to UCS ratio of 0.35 (ranging from 0.3 to 0.4), for a

group of 23 samples collected in locations near of Istanbul (Turkey); their UCS values were between 53 MPa and 149 MPa. In the present study, the range of values for the ratio of CI to UCS in limestone is between 0.3 to 0.6 and aligns well with previously published ranges. The CI values for marly (PA: 0.4) and micritic (PA: 0.45; PE: 0.42) limestone of Member I from Thebes Formation tested in this research represent the first CI values published to date for this Formation.

5.8 Discussion

5.8.1 Quality of Reported Data and Overall Results

The examination of the available literature and the analysis of results from Section 5.7.2 suggest that sample description and standardized tests have been scarcely reported so far. This poses a challenge for data comparison and validation and if literature values were to be used, e.g., in rock-mechanical calculations. In particular, the use of standard testing procedures (international or other) should be well documented in future testing programs. To the authors' knowledge, this study presents the first documentation of thermal properties and critical crack threshold (i.e., CC and CI) for the KV, and data of these properties could be used in the study of environmental fluctuations inside tombs with rock wall cracking in the KV, such as the continuing research carried out by Alcaïno-Olivares et al. (2020), Hemeda (2021) and Khalil (2017).

Any rock sampling and testing program within the KV represents a rare opportunity due to the restrictions imposed by the Egyptian authorities to preserve this UNESCO World Heritage site. In order to expand the database of properties for the Thebes Limestone Formation, sample collection should also be performed in a rigorous manner not only to document the location of the samples but also to consider the samples' time history to ensure that samples that are compared underwent similar environmental processes (e.g., wetting and drying cycles, thermal fluctuations). Ideally, the structure of collected samples and their state in terms of microdamage related to, e.g., thermal fatigue or swelling processes should be assessed with microscopic or computer tomography analyses. For instance, the marly limestone tested in this work was classified as water sensitive as part of the rock classification in Table 5-2, however no dry coring was available during the testing program. Although the water used was minimized to ensure the core drilling and the integrity of the sample, whilst those samples severely affected by the water were not considered in the tests. In addition, other techniques for determining the porosity (e.g., total porosity measurements) could have been used to avoid the water in contact with samples, although the method used in this research fit the availability of equipment at the time of the testing program. Furthermore, the rock block descriptions detail

the macroscopic features and heterogeneity (e.g., fractures perpendicular to bedding planes, presence of silica nodules and bands, and clay minerals) of the blocks that were cored to take our samples from, to ensure that large features could be avoided during the core sampling processes, so that the results represent the intact rocks parameters, which can be compared well with each other. Comprehensive sample descriptions are important to document in order to continue to build a reliable database of engineering properties within the KV.

5.8.2 Petrophysical and Mechanical Properties

Bedded sedimentary rocks typically exhibit anisotropic petrophysical and mechanical properties (Bagheripour et al., 2011). In this testing program, special attention was paid to the orientation of bedding planes, quantifying the degree of anisotropy and its effect on the strength of the marly and micritic limestone. Two criteria were applied: the ratio of UCS PA to PE (the R_c index of Ramamurthy (1993)) and the transversely isotropic elastic constants (the n index of Kwasniewski (1983)). The latter was only applied to the micritic limestone, because no valid tests and elastic parameters could be obtained for the PE samples of the marly limestone. Ramamurthy's (Ramamurthy, 1993) criterion classifies marly limestone as fairly anisotropic (i.e., $R_c = 1.3$). Micritic limestone is classified with index values from medium (i.e., $R_c = 2.4$) to low anisotropic (i.e., $n = 2.1$) using both methods. Hence, both lithologies exhibit a transversely isotropic stress–strain behaviour.

As part of the literature background, it was described that water in contact with Member I is a concern for the rock behaviour (i.e., because of nature of water-sensitive clay minerals, also known as ISRo). Although our research focused on dry mechanical tests, the slake durability results (I_d) could offer valuable information on the water sensitivity of the samples. The marly limestone was classified as highly durable, whereas the micritic limestone yielded an extremely high slake resistance according to Franklin and Chandra (1972). The lower slake resistance for the marly limestone than micritic limestone relates to the large percentages of ISRo minerals reported to this unit (King et al., 2017). The effects of the ISRo relate to the marly limestone features observed in the retained fragments, such as layer expansion, surface cracks, and cavities in large edgeless pieces when the rocks were submerged in water. Small fragments (>2 mm) were long and thin sheet-like pieces. The micritic limestone retained fragments were more rounded and polished, and no small chips or slabs were seen as a result of water intake and mineral expansion. Furthermore, the characteristics of the retained fragments support the observation that the slaking durability reflects the strength of sedimentary rocks. Some authors have suggested that the lower the I_d , the lower the UCS (Sharma and Singh 2008, Yagiz

2011), which aligns with our findings (i.e., marly limestone had both the lowest I_d and UCS). Nevertheless, progressive exposure to slaking cycles and the loss of strength has not yet been studied for Member I, which could help to understand the impacts of flooding events on tomb wall stability.

Several authors have suggested that the variability in the mechanical response under loads relates to both rock petrophysical properties and the degree of intact anisotropy (Zhu et al. 2010, Altindag 2012). Various geotechnical properties of marly and micritic limestone are compared in scatter plots in Figure 5-9 in order to illustrate the variability. The discussion in terms of petrophysical properties is based on the reported V_p values. For instance, a transverse isotropic behaviour can be seen when plotting UCS against V_p (Figure 5-9a). The anisotropy relates to the nature of bedding planes, as tested by other authors (Lazar 1995, Wüst 1995, Wüst and McLane 2000, Hemeda 2021). This causes the reduction in wave speed for PE tests, in comparison to PA tests, because of samples are less continuous cross the planes, whereas the V_p for PA tests, the bedding acted as a path for the ultrasonic waves, thereby increasing the wave speed over the PE samples. This difference was highlighted by Xue et al. (2014) in their tests in the PE orientation, which withstood higher strains and resulted in higher strengths than in the PA orientations.

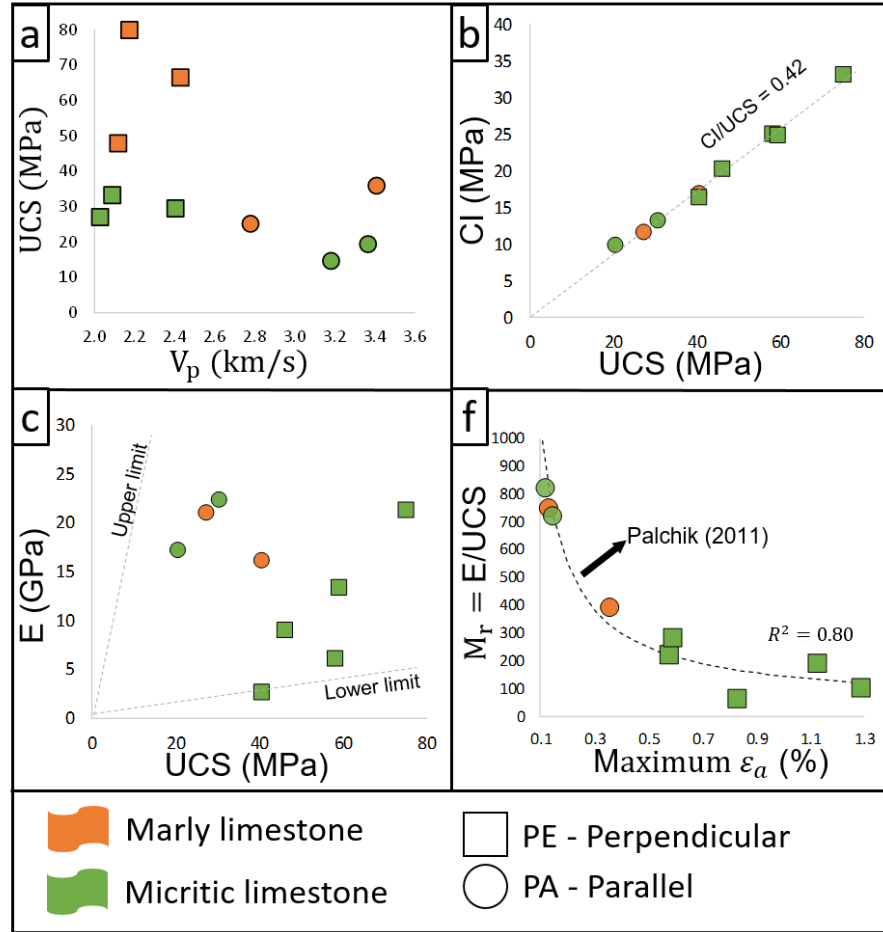


Figure 5-9: Correlation between parameters measured in this research. Symbols for geotechnical properties are illustrated in Table 4. (a) Unconfined compressive strength versus P-wave velocity; (b) crack initiation versus unconfined compressive strength (c) Young's modulus versus unconfined compressive strength. Upper and lower limits for UCS vs. E are plotted (Hoek and Diederichs, 2006); (d) modulus ratio versus maximum axial strain. Correlation of data plotted as dashed line (Palchik, 2011).

For the crack initiation (Figure 5-9b) and elastic parameters (Figure 5-9c,d), both the PA and PE orientations followed trends reported in the literature (Perras and Diederichs 2014, Hoek and Diederichs 2006, Palchik 2011). The CI threshold showed that data for all PE and PA followed a linear relationship ($R^2 = 0.99$), with a slope (i.e., ratio of CI to UCS) of 0.42. This CI/UCS ratio was within the typical limits of 0.3–0.5 (Perras and Diederichs, 2014), and the data of the CI/UCS ratio (shown in Figure 5-8) showed little influence of the bedding orientation. The elastic stiffness (E) and peak stress (UCS) are plotted in Figure 5-9c. The upper and lower boundaries are defined by the ratio of E to UCS of published data, also known as the modulus ratio (MR) (Xue et al., 2014). All tests had an average MR of 393, which is close to the mean value proposed by Deere (1968) for limestone and dolomites ($MR = 420$) and Palmström and Singh (2001) for limestones ($MR = 441$). The PE-oriented tests yielded a mean MR value of 171

(ranging from 61 to 279), whilst the PA orientation MR values were 679 (ranging from 391 to 817). Hoek and Diederichs (2006) pointed out that higher values of MR are expected when force occurs in the PA orientation than in the PE orientation, as seen in our results due to the transverse isotropy of the rocks. In fact, only the PA orientation met the proposed range of MR for micritic/sparitic limestone from 400 to 1000, as reported by Hoek and Diederichs (2006). The PE results fall below the lowest boundary though remained within the broad range from 100 to 1000 for limestone literature values (Xue et al. 2014, Deere 1968, Palmstrom and Singh 2001, Li and Villaescusa 2019). To address the broad range MR values in the literature, Palchik (2011) tested and compiled information for a large number of carbonate sedimentary units from Israel (limestone amongst them), defining a dependency of the MR to the maximum axial strain. The proposed correlation from Palchik (2011) aligned well with the results presented here, with an $R^2 = 0.8$, as shown in Figure 5-9d (dashed line). The maximum axial strain of our test results indicates a clear distinction between bedding orientations, though it appeared to be independent of lithology in the current study.

In rock engineering projects, mechanical properties are used in empirical design criteria or in numerical models as inputs into failure criteria. The definition of a failure criteria becomes more complex when the loads originate from a combination of different sources (e.g., gravitational, thermal, and hydraulic). For instance, Woodman et al. (2021) studied the thermomechanical loading of intact samples of sedimentary isotropic rocks (sandstone) at temperatures lower than 100 °C by triaxial tests and numerical models. The authors found a reduction of up to 15% of the peak strength with increasing temperatures from 20 to 100 °C, and the effect of localized thermal stresses triggered tensile micro cracks that contributed to a reduction in strength. Woodman (2020) pointed out that this process is delayed when structures (e.g., beddings or natural fractures) exist in the samples, as the thermal expansion of discontinuities causes thermal closure, and intact material failure resumes after the maximum closure of the discontinuities is achieved. This idea is supported by the work of Marmoni et al. (2020), who studied the thermomechanical fluctuations in rock slopes. The authors found that discontinuities interrupt the heat transfer process, dissipating heat or dilate the discontinuities planes. In particular, to KV, the water incidence has been pointed out as one of the biggest challenges when dealing with Member I Thebes Formation, particularly for our marly limestone samples, and its swelling and shrinking cycles have largely affected the landscape and the rock-cut constructions in KV, which according to several authors is one of the main hazards in the area (Rutherford 1988, Hamada et al. 2004, Wüst and McLane 2000, Hemeda 2021, Khalil 2017). Therefore, the integration of different loads and strength-

degradating factors to anisotropic rocks could provide a more realistic assessment of the stability of the rock masses. Such considerations are necessary in real-world scenarios, such as the study of the decorated tombs in the Theban Necropolis (Hamada et al. 2004, Wüst and McLane 2000), the stability of cliffs surrounding the KV (Alcaino-Olivares et al., 2020), and other sites worldwide (Marmoni et al. 2020, Collins et al. 2018, Alcaino-Olivares et al. 2021). Future testing should include both the petrophysical and mechanical properties, with particular attention paid to degree of weathering, clay mineralogy and its influence on swelling, as well as anisotropic and thermal influences.

5.9 Conclusions

A characterization of the intact anisotropic rock properties of limestones collected from the Valley of the Kings is presented in this article. A testing program was conducted to develop a comprehensive set of numerical model input parameters and to benefit geotechnical work in the KV for future preservation measures of this UNESCO World Heritage site. We highlight this unique opportunity of sampling rocks inside the KV. To our knowledge, this work represents not only the first exhaustive documentation of intact rock properties for the marly and micritic limestone from the Member I of the Thebes Limestone Formation but also provides a first analysis of crack initial thresholds, which are important properties for long-term stability considerations. Our findings are compared to the limited information in the literature regarding the Thebes Limestone Formation.

The geotechnical properties were measured parallel (PA) and perpendicular (PE) with respect to the bedding planes. The marly and micritic limestone exhibit transverse isotropic strength behaviour, with the bedding plane acting as an isotropic plane, typical of sedimentary rocks. The results of UCS tests show that the micritic limestone average strength for PA orientation is 24 MPa, whilst PE tests are 58 MPa. According to the classification set by Ramamurthy (1993), the rock unit has a low anisotropy. Similarly, the marly limestone samples had an average strength of 30 MPa for PA tests and 39 MPa tests, classified as fairly anisotropic, based on similar criterion. Elastic constants also vary in the PA and PE orientations. We also classified the anisotropy of the micritic limestone samples using an approach based on elastic constants formulated by Kwasniewski (1984), where the Young's modulus (E) measured in PA tests are 20 GPa, whilst PE tests showed 10 GPa. The Poisson's ratio (ν) values are 0.2 for PA tests and 0.1 for PE tests. This suggests a medium intact anisotropy of the micritic limestone (Ündül et al., 2016). The volumetric strain (i.e., combination of lateral and axial strains) approach was preferred to avoid biased results because of bedding plane splitting gauges and/or causing erratic lateral strain readings. This is suggested for any intact anisotropic rock testing program.

Accordingly, the CI threshold showed that the CI values for the marly limestone are 14 MPa for PA tests, and the micritic limestone for PA tests is 11 MPa and PE tests is 24 MPa. Both rock types fall within published values, typically expressed as the ratio of CI to UCS (e.g., 0.36–0.52). The average value of PA and PE samples were 0.43 and 0.42, respectively.

Robust geotechnical properties that include rock anisotropy and lower strength thresholds, i.e., CI values, are essential for providing rock engineering solutions through empirical, analytical, and important numerical modelling approaches. In particular, for anisotropic rocks, the stiffness of different composing layers can guide the mode of failure such as the development of axial fractures and local shearing along bedding planes. The intact rock properties described in this paper will be used at the rock mass scale to numerically model cliffs and tombs in the KV to better understand deformation measurements collected by the authors that could be related to damage progression over long period of time. There is potential to validate a failure criterion for long-term stability assessments, which can incorporate the CI threshold. The application of these results will lead to new insights regarding anisotropic rock mass behaviour and long-term stability, which in turn will help develop a better understanding of other influencing factors on the stability of cliffs and tombs in the KV, ultimately leading to better preservation approaches for this rich UNESCO World Heritage site.

CHAPTER 6 MONITORING AND MODELLING THE THERMALLY ASSISTED DEFORMATION OF A ROCK COLUMN ABOVE TOMB KV42 IN THE VALLEY OF THE KINGS, EGYPT

6.1 Preface

This chapter introduces the instrumentation of the studied rock column in the Valley of the Kings that was used to investigate in situ the impact of thermo-mechanical processes on the rock mass deformation and stability. The data collected at the site were analysed and incorporated into a site-specific bi-dimensional (2D) model in FLAC®. The numerical model delivered fracture opening values under thermo-mechanical conditions that aligned with measured data, as well as helped in comprehending the relationship between the geometry, joint presence and thermal boundaries. The content of this chapter was published in *Rock Mechanics and Rock Engineering* in 2023 as follows:

Alcaíno-Olivares, R., Ziegler, M., Bickel, S., Leith, K. and Perras, M.A. (2023) Monitoring and Modelling the Thermally Assisted Deformation of a Rock Column Above Tomb KV42 in the Valley of the Kings, Egypt. *Rock Mechanics and Rock Engineering*, 56 (11), pp. 8255–8288. <https://doi.org/10.1007/s00603-023-03458-1>

Author contributions are listed such as: **conceptualization** (Alcaino-Olivares, Ziegler and Perras), **data curation** (Alcaino-Olivares, Ziegler and Perras), **formal analysis** (Alcaino-Olivares, Ziegler and Perras), **funding acquisition** (Perras), **investigation** (Alcaino-Olivares, Ziegler, Perras and Bickel), **methodology** (Alcaino-Olivares, Ziegler and Perras), **project administration** (Bickel), resources (Ziegler, Perras and Bickel), **writing-original manuscript** (Alcaino-Olivares) and **writing-review and editing** (Ziegler, Perras, Leith and Bickel).

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for their simulated data from 1985 for the Luxor region. The **Metropolitan Museum of Art of New York City** has granted access to the Harry Burton's archives, so we recognize the contribution from **Aude Semat** and the Egyptian Art members at the MET to this research. Finally, we highlight the support in part from Natural Sciences and Engineering Research Council of Canada (NSERC) through the Discovery Grant program [RGPIN-2018-05918] and in part by funding from the Government of Canada's New Frontiers in Research Fund (NFRF), [NFRF-2020-00893].

6.2 Abstract

The Valley of the Kings (KV) is located within a large funerary landscape called the Theban Necropolis, in Luxor, Egypt. In 2018, our team started to monitor the transient conditions of a 15 m rock column of micritic limestone above the tomb KV42 and a fracture located at the west end of the column (lateral fracture), registering thermo-mechanical displacements with a crack meter, infrared thermographic sensor, and a weather station. The data from April 2018 to May 2021 showed seasonal fluctuations in the rock surface temperature (RST) from 12°C (winter) to 45°C (summer), as well as an average reversible fracture opening (FO) rate of 1 mm/year. The measured average thermo-mechanical ratio of FO to RST was 0.05 mm/°C. Data collected at the site were used to calibrate a finite difference model in FLAC®8.0 for thermo-mechanical simulations. The results showed a correlation (R^2) of 0.8 between measured data and elastic isotropic mechanical constitutive model results, with a ratio of FO to RST equal to 0.03 mm/°C and rates of reversible displacements of 0.8 mm/year, whereas the average irreversible displacement for the monitored period of 2018–2021 was 0.2 mm/year. The insights from this study can help provide a preservation approach for this area of the UNESCO World Heritage site and also enhance our understanding of environmentally driven long-term fracture growth mechanisms, such as thermo-mechanical fatigue. In the future, such insights could become more important as the global and local magnitude of daily and annual temperature fluctuations continue to increase.

6.3 Introduction

The Theban Necropolis is an ancient funerary landscape located in the south-central part of Egypt, on the West Bank of the Nile River (Figure 6-1). The site was mainly used during the New Kingdom (3500–3000 BP), and its vast archaeological richness with more than 450 underground tombs has earned the area the designation of a world heritage from UNESCO in 1979. The Valley of the Kings (or King's Valley, KV), a sub-cemetery in the northern area of this UNESCO site, was chosen during the New Kingdom for the rock-cut sepulchers of the pharaohs (kings) and some of their family and entourage. The walls of the underground chambers of the royal tombs are decorated with paintings and reliefs that were destined to accompany the king's sojourn in the afterlife (Reeves and Wilkinson 2008, Wilkinson and Weeks 2016). Royal burials were also equipped with a variety of valuable goods such as jewelry or gilded objects, most of which were looted in Antiquity already. Since the nineteenth century, the KV has become a major tourist attraction and a site of archaeological interest. To date, sixty-four tombs have been uncovered in the KV; the total number of tombs remains unknown.

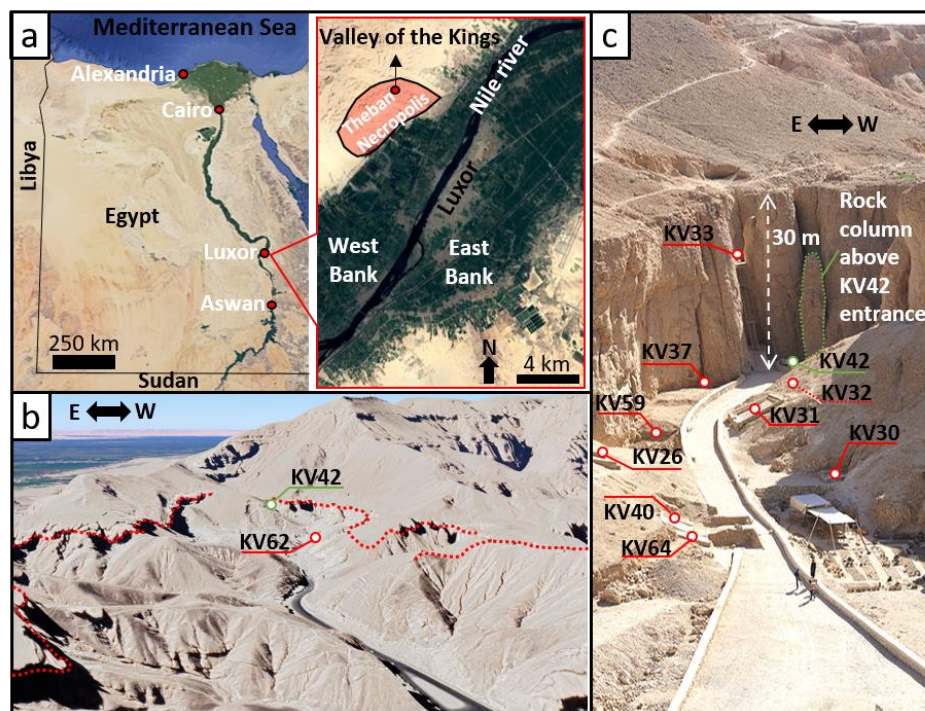


Figure 6-1: Images of the study area showing a) the geographical location of the Theban Necropolis within the African continent, Egypt, and Luxor, as well as b) a satellite photograph of the Valley of the Kings (KV), highlighting the valley's cliffs (red dashed line), the tomb KV62 (Tutankhamun) in the central section of the KV and the tomb KV42 in the southern branch of KV. Pictures taken from Google Earth imagery date 23rd January 2022 (Google Earth Pro 2022). c) Southern branch of the Valley of the Kings with approximately 30 m tall cliffs surrounding the tomb entrances (KV#), (courtesy of Matjaz Kacicnik). The rock mass is cut by two sets of subvertical joints forming rock columns, seen above tomb KV42, where a sensor has been installed to monitor the movement of the rock column western edge from the gorge walls, so-called lateral fracture.

The KV is part of a valley (wadi) system (Figure 6-1b), with tall (20–30 m), sub-vertical (70–90°) to partly overhanging cliffs of marl and limestone belonging to Member I of the Thebes Limestone Formation (Lukovic et al. 2021; Alcaïno- Olivares et al. 2022). This morphology creates a basin of 45 ha, which during sporadic rainfalls led to flash floods in the past. These are the major hazard towards conservation in the KV (McLane and Wust 2000, Paulose 2020). For instance, the narrowest sections of the KV are located at the southern end, with the highest (30 m) and steepest (85°) cliffs forming a gorge approximately 40 m wide at its base. This 40 m wide section encloses pedestrian paths, excavation areas, and tombs (Figure 6-1c). Sediments accumulate on the floor of gorges during intense rainfall events (Dorn et al. 2015). Hence, in general, for the KV, restoration campaigns have been undertaken, to prevent both sudden and progressive cliffs' collapses, which have been classified as Medium Risk factor by the site management masterplan for KV (Weeks and Hetherington 2006). Particularly hazardous are those sections around the tomb KV42 (25°44'17.1"N, 32°36'2.6"E; KV# stands for King's Valley tomb #), where a tall, isolated rock column (15 m from current ground level) stands above the entrance of the tomb. The rock column is formed by a NS striking lateral fracture, with a rate of propagation previously estimated as 20 mm per year, leading to the crumbling of the column that could result in fatalities as well as loss of archaeological evidence (Cross 2008a). However, no processes explaining the progressive failure mechanism of the column were suggested. Numerical modelling for assessing only gravitational stress and fracture orientation indicated that the column is stable (Alcaïno-Olivares et al. 2019, Maissen 2019), yet transient models incorporating thermally induced stresses from weather conditions have shown the potential for rock temperature fluctuations driving displacements of the lateral fracture (Alcaïno-Olivares et al. 2020).

Thermally assisted deformations in jointed rock masses have been studied in the last decades using theoretical and numerical approaches. However, there is not a clear consensus on the driving mechanisms at the rock mass scale that lead to either reversible (i.e. rock mass oscillations) or irreversible displacements (i.e. fracture extension and failure). A summary of the site investigations conducted in the last 20 years is presented in Table 6-1, only for research which focuses on thermally driven mechanical displacement modelling.

Table 6-1: List of on-site investigation for thermo-mechanical rock mass behaviour conducted across several locations worldwide. Note: the table is a shorter extraction from Table 2-1, filtered by those authors who achieved to develop a model for their investigation.

Rock Type	Location	Morphology	Model developed	Main conclusion	Reference
Sedimentary	Masada National park, Israel	Block displacement from steep cliffs in dolomite limestone.	TM-2D. Theoretical	Variation of displacement linked to fluctuation of air temperature. Compared to seismic forces, historic displacements of 200mm is more likely to have been thermally induced.	Bakun-Manzor et al. (2013)
	Vercors Massif, France	Rock column 30m height, 15m wide and 5m thick (1000m ³) in marly limestone.	TM-2D. Numerical (COMSOL)	Freeze and thaw processes lead to changes in vibrations. Temperature has an inverse trend to vibrations with a delay of 3 months, possibly due to thermal expansion.	Botellin et al. (2013)
	Czech Republic, Bohemian Switzerland	Rock arch, min. tie beam thickness 2.5m, span 26.5m in sandstone.	TM-2D. Numerical (UDEC)	Temperature oscillations produce changes in stresses due to expansion and contraction, leading to reversible displacements.	Vlcko et al. (2014)
	Acuto quarry, Italy	Abandoned quarry, slope facing S and E. Limestone.	TM-2D. Numerical (FLAC®)	Role of open joints in the heat propagation within the rock mass. Numerically modelling for the effect of daily and annual weather conditions in the long-term evolution of fractures.	Marmoni et al. (2020)
	Roque Gageac, France	100 high cliffs. Limestone.	TM-2D Theoretical	Subcritical crack growth is influenced by weather fluctuations at to a depth of 6m to generate large fractures.	Gasc-Barbier et al. (2021)
Igneous	Daisetsu Mountains, Japan	SW slope, vertical and horizontal joint network. Andesite.	TM-2D. Theoretical.	Temperature cycles can lead to fatigue and brittle failure, since normal stress at crack tip exceeds fracture toughness.	Ishikawa et al. (2004)
	Iwate, Japan	Rock slope, dipping >65°SW. "Chert" blocks highly jointed	TM-2D. Empirical.	Thermal cycles contribute to brittle failure, increasing stress concentration at crack tip, and performing inverse cycles with measured displacements.	Mufundirwa et al. (2011)
	California, United States	Rock slope is 500m in height, studied slab is 19m tall by 4m width, and 10cm thick. Granodiorite (exfoliation sheet)	TM-2D. Theoretical.	Bedrock are dynamically affected by temperature cycles which can increase the stress intensity to trigger cumulative of opening of fractures.	Collins and Stock (2016)
	California, United States	Rock bridges which hold slabs to a steep rock slope (500m). Granite.	TM-1D. Theoretical	Air circulation cool down sides of slabs close to rock bridges, registered as thermal anomalies by IRT. Potential use to assess structural state of rock masses	Guerin et al. (2019)
Metamorphic	Southern Alps, France	Slope of 50m in height and dipping 45°SE. Gneiss.	TM-2D. Theoretical	Temperature fluctuation may assist slope failure. Theoretical model helps understand plastic deformations of joints.	Gunzburger et al. (2005)
	Randa, Switzerland	Translational landslide, 500m in height at 50°. Gneiss.	TM-2D. Numerical (UDEC)	Progressive irreversible deformation is triggered by thermal cycles, due to critically stressed discontinuities. TM effects is more effective in more competent rock mass.	Gischig et al. (2011)
	Rio de Janeiro, Brazil	Abandoned quarries with slopes up to 30m. Fine grained gneiss and coarse granite.	TM-2D. Empirical.	Evidences of thermal cycles and slope failure are collected qualitatively. Laboratory test in rock blocks help understanding effect of local weather in creating cracks	Vargas et al. (2013)
	Baltic Sea, Finland	Sudden fracturing in a rock dome in an island. Microcline granite.	TM-2D. Numerical (FLAC®)	Fracturing events can be numerically modelled as a result of temperature fluctuations with rates between 0.03 mm/°C and 0.06 mm/°C.	Alcaino-Olivares et al. (2021)

Thermo-mechanical displacements can occur in a wide range of lithologies and climatic conditions, however, many research groups take different approaches to data processing and modelling. In some cases, theoretical models are focused on rock mass deformations that result from intact rock deformations, neglecting the presence of joints. Other approaches may fail in incorporating the transient state of the environmental fluctuations. Nevertheless, they all agree to the importance of data acquisition during long time-frames to better assess the time-dependent behaviour of the rock mass. Hence, the effect of factors that influence weather on rock mass deformation remains a scientific gap to study the thermo-mechanical effects in the long-term.

In this study, we present climatic and fracture opening data alongside numerical models designed to reproduce deformations of the rock column above KV42. The goal of our investigation is to evaluate the influence of transient climatic conditions on processes driving the propagation of a large lateral fracture between the rock column and the adjacent cliff. A monitoring system installed in April 2018 tracked the relative motion across this lateral fracture. The system includes a crack meter, infrared thermography, rock and air temperature and relative humidity sensors. In this article, the first of two complementary studies, we present technical details of the installed monitoring system and the methodology used to input natural thermal cycles into a 2D numerical finite differences model (FDM) in FLAC®. We gather evidence of the thermo-mechanical behaviour of the rock mass, supporting the observational existence of a thermally assisted near-surface rock fracturing mechanism from a macroscopic perspective aiding the growth of this lateral fracture. Our work aims to model a subcritical condition for failure assisted by thermally induced strains, highlighting the methodology of how to incorporate key variables into a numerical simulation for heat exchange, thus simulating thermo-mechanical deformations. Furthermore, the understanding of the modelling constraints to replicate transient thermo-mechanical behaviour of rock masses is of relevance for further 3D modelling stages in our work.

6.4 Case Study: The Cliff Above KV42

6.4.1 Archeological Significance of KV42

The tomb KV42 is located at the southern side of the KV, amongst some of the oldest burial places prepared for pharaohs and royals from the 18th Dynasty (3470–3350 BP). The architecture of KV42 is like contemporary tombs, known as cliff-tombs, with a main entrance excavated at the toe of a cliff, with steep stairs and corridors followed by an oval chamber with two pillars. The tomb was explored by Chinouda Macarios and Boutros Andraos in 1900, with Howard Carter as a chief inspector who reported in his notes that the tomb had been robbed and damaged in ancient times (Reeves and Wilkinson 2008). In 1999, KV42 was re-cleared under the direction of Mohamed El-

Bialy, showing evidence of past flooding events, marked by washed floors and the presence of yellow mud, which is a common feature in ancient cliff-tombs (Willockx 2011, and references therein).

Although protection barriers against tomb flooding were constructed already in ancient times (i.e. 3500–3000 BP), these did not always prevent water from entering tombs. Most of the constructions had either deep shafts or flights of inclined corridors. Over time the ancient Egyptians did identify new hazards in an empirical manner (Dorn et al. 2015), however, the tombs were only protected by the construction of small dams nearby to diminish the consequences of flash floods (Cross 2008b). A comparison of photographs (Figure 6-2a,b), taken in 2019 by our team and 1910 by Harry Burton (Burton ca.1910), shows the original accumulation of debris as a result of water streams at an elevation of approximately 3 m above the current pedestrian path (today, 6 m from the tomb's entrance), which has been lowered after several excavation and rehabilitation works in KV. Other structural features are labelled for comparison purposes, such as the three rock slabs and a bottom section (called the notch section) on a 15 m tall rock column (above the KV42 entrance). Sub-vertical joints on a taller cliff behind the studied column are still present and the associated rock blocks remained in place. Despite that these features remain intact, the valley has suffered from flash floods during the last century with catastrophic consequences, such as the torrential rain in 1994 which lasted 2 h with an intensity of 16 mm/h. This event caused damage to tombs and archaeological work. Hydrological studies indicate that the return period for a 2-h event is of the order of 25 years for 16 mm/h, 50 years for 22 mm/h and 100 years for 30 mm/h (Ogiso et al. 2017). However, the current surficial landscape seems to date back to at least 1999 (Weeks and Hetherington 2006).

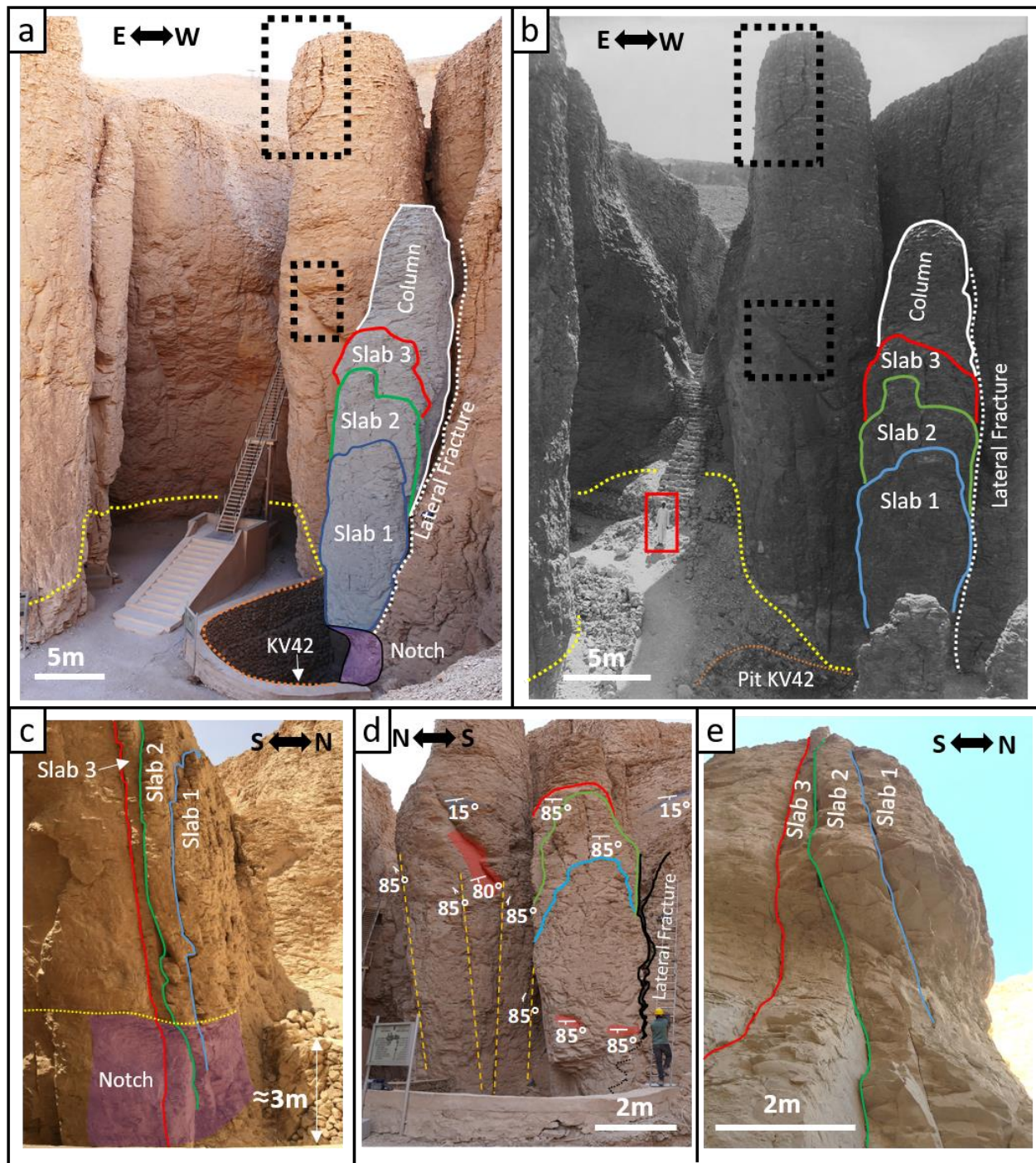


Figure 6-2: Important features of the surrounding rock mass and rock column above KV42, highlighted in a) panoramic view of KV42 exterior (taken in 2019), showing a lateral fracture (pointed white line), rock slabs (blue, green and red lines), rock column (white line), notch section (purple), pit of KV42 (orange dashed line) and level of the debris prior to the tomb excavation (yellow dashed line). Structural elements of the taller column behind the studied rock column are highlighted in dashed black rectangles. Historical pictures were collected, which show similar structural elements, such as in the oldest visual register b) from Harry Burton c.a. 1910 (MET archives, photo T1330). The extension of the three joints generating slabs (i.e. J1, J2 and J3) are visible in a c) SN profile picture (facing westwards) with an average spacing of 0.5 m; along with d) identification of the most pronounced joint set in the area, as well as e) slab 2 and slab 3 extending deeper in the ground (picture looking upwards).

6.4.2 Geotechnical Characterization of the KV42 Rock Column

The Valley of the Kings is a 400 m EW by 600 m SN valley located in the northern section of the Theban Mountains (Lukovic et al. 2021). The studied rock column is in the most southern branch of the valley, a gorge of 40 m wide EW by 180 m long SN as shown in Figure 6-1b. The cliffs surrounding the Valley of the Kings belong to the Member I of the Thebes Limestone Formation (Lower Eocene) (Said 1990). This member contains mostly micritic limestone above 180 m a.s.l. (Alcaino-Olivares et al. 2022), which changes in colour from beige (slightly weathered), to tan and even cream (fresh fractures). Bedding planes are oriented 200/15 (dip direction/dip angle) (Lukovic et al. 2021, Maissen 2019), with chert flints and elongated bands of silica (< 20 cm length) usually orientated along the bedding planes. The presence of bedding planes explains the existence of rock-mechanical anisotropy (transverse isotropic behaviour), which is reported as medium in terms of strength and as low for elastic stiffness (Alcaino-Olivares et al. 2022). The geotechnical and thermal properties of the micritic limestone are summarized in Table 6-2. At the top of Member I at about 220 m a.s.l. a nodular limestone occurs (Wüst 1995).

Table 6-2: Rock mechanical (physical and strength limits) and thermal properties of micritic limestone, after Alcaino-Olivares et al. (2022).

Property	PA			PE		
	#	Average	Min–Max	#	Average	Min–Max
Thermal conductivity (W/m ² K)	3	0.72	0.52–1.07	2	0.65	0.66–0.65
Volumetric specific heat (MJ/m ³ °K)	3	1.56	0.83–2.34	2	1.62	1.36–1.87
Bulk density (kg/m ³)	13	2074	1787–2247	34	2057	1664–2926
Apparent porosity (%)	3	15.8	13–17.8	11	18.6	13.7–23.9
P-wave speed (km/h)	5	3.22	3.06–3.37	9	2.20	2.05–2.46
Tensile strength (MPa)	7	8	1.9–13.4	11	6.7	4.9–8.9
Uniaxial compressive strength (MPa)	5	15.6	6.4–21.0	9	55.6	40–79.9
Young's modulus (GPa)	2	17	–	6	10.13	5–19
Poisson's ratio, unitless	2	0.21	0.1–0.31	6	0.11	0.08–0.13
Crack closure (MPa)	2	7.5	7.5–7.6	6	10.7	6.3–20.7
Crack initiation (MPa)	2	13.2	13.0–13.4	6	21.7	13–33.5

The rock column above KV42 is 18 ± 0.5 m tall (from the tomb's entrance, 15 ± 0.5 m from the current ground level), 3.5 m wide, and 4.1 m thick. The column contains three sub-vertical slabs (S#, in Figure 5-1 and 5-2) on its northern face with orientations of $000/85 \pm 5^\circ$, which are separated by open fractures with an aperture of up to 1–3 cm at the upper section and have thicknesses of S1: 0.4–1.0 m, S2: 0.5–0.6 m, S3: 0.4–0.5 m (Maissen 2019). The full size of the slabs is not clear, except for slab 1 which terminates above a notched section. S2 and S3 extend straight, deeper below the ground with an unknown depth and persistence (Figure 5-2c). A fracture of

tectonic origin separates the back cliff (height 30 ± 2 m, from KV42 entrance) and the west side of the rock column, as shown in Figure 6-2a,d.

This so-called lateral fracture strikes SN with a variable inclination from vertical on top to stepped at the bottom. The aperture and infill of the lateral fracture can be described from the ground floor, with the fracture being fully closed at an elevation of 2 m. Between 2 and 3 m of elevation, the fracture aperture is less than 2 cm, with infills of clayey-sand-sized particles. At an elevation between 3 and 7 m, the lateral fracture holds rock debris (i.e. cobble and gravel size) so that its aperture extends about 10 – 20 cm in length. Above 7 m, the lateral fracture is open and clear, no infills are held in this region and the aperture increases from 15 cm to approximately 1 m at the very top of the column. The most pronounced joint sets in the column corresponding to the slabs at $000/85 \pm 5^\circ$ and a perpendicular set oriented $180/85 \pm 10^\circ$, in addition to the bedding planes $200/15$ (Maissen 2019), as shown in Figure 6-2d. The average geological strength index (GSI) of the entire rock column varies from 50 to 75, with the notch section in the low range.

The notch (bottom) marks the ground floor level before the excavation of KV42 in the early twentieth century (i.e. covered by colluvium), and field inspections showed that sediments such as silty-sand and limestone flakes do exist on the notch surface which might be related to flooding events (Figure 6-2d). Similar notch features are seen in other locations within KV, varying in vertical extension and always located at the toe of cliffs (Lukovic et al. 2021).

The vertical extension of the lateral fracture reaches into the notch section. The open fractures defining the slabs allow for a complex toppling mechanism. However, no striation or other evidence of sliding has been observed. To assess whether further opening of the lateral fracture tip occurs, our team placed gypsum marks close to the lateral fracture tip in 2017. To date, these marks remain intact which indicates no opening of this fracture since this date. An assessment of local seismicity acquired on-site (with a Raspberry Shake 4D installed at the entrance of KV42) did not deliver any link between 32 events with peak ground accelerations below $7 \cdot 10^{-4} \text{ m/s}^2$ and the lateral fracture opening (Maissen 2019).

6.4.3 Climatic Conditions of the Valley of the Kings

Egypt is located within the Middle East and North Africa region, with a hot desert climate according to the Köppen–Geiger classification. However, precipitation in the Luxor region is almost non-existent with no recorded precipitation for periods extending several years (e.g. 1951–1958, 1960–1963, 1975–1979, 1984–1988, 1995–2000) (Paulose 2020). Summer typically lasts from May to October, whilst winter extends from December to February. Climate change

studies in Egypt indicate that these seasons may be changing in length, with longer summers and shorter winters (e.g. Nashwan et al. 2019, El-Hagrsy et al. 2018, Aboelkhair et al. 2019). Historical meteorological data for the region can be obtained from the Luxor Airport station ($25^{\circ}40'25.72''\text{N}/32^{\circ}42'5.47''\text{E}$) located 13 km south-east of KV with the oldest records dating back to 1943. The station reports air temperature, wind speed and rainfall, however, the data set contains a large amount of missing data prior to 1985, as shown in Figure 6-3a (e.g. 1949–1952, 1960–1964, 1965–1973). Air temperatures at the airport station commonly range from 5 to 45°C throughout the year, whilst average daily air temperatures range between 15 and 30°C , with a consistent 10°C diurnal variation (Figure 6-3b).

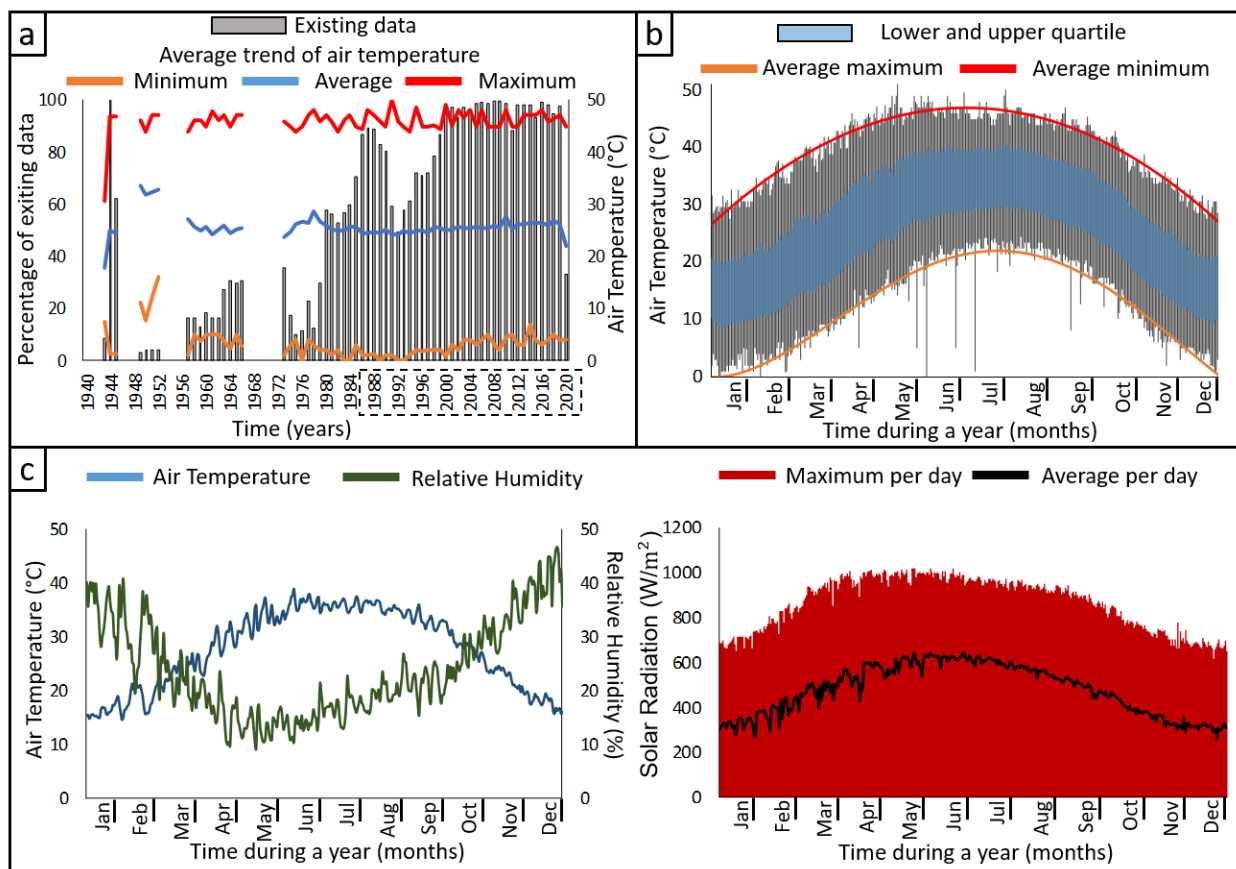


Figure 6-3: Environmental data from a) the weather station at the Luxor Airport (Egyptian Meteorological Authority, 2021), with average annual data since 1985; including the b) box plot for lower and upper quartile of air temperature, and maximum and minimum average trends throughout the year on daily basis. Locally, a summary of c) data collected by the Helio Scientific group in the Valley of the Kings at KV62 (personal communication), showing the day-by-day averages of the years 2016 to 2019 for air temperature, relative humidity, and solar radiation (daylight hours only).

In the Valley of the Kings, both interior and exterior weather conditions, at tomb KV62 (Tutankhamun's tomb, $25^{\circ}44'24.8''\text{N}/32^{\circ}36'4.8''\text{E}$, located 240 m North of KV42) have been monitored since 2016 by Helio Scientific (pers. comm. Helio Scientific 2019). The daily average

of the data is introduced in Figure 6-3c, showing an average air temperature of 30°C during a 4-month period (May to August), with the lowest value of 15°C (December, January). The relative humidity (RH) reaches a minimum value of 10% between June and August, rising up to 45% for the colder months (i.e. November to January). The maximum solar radiation (SR) values range from 1000 W/m² (summer) to 700 W/m² (winter), whereas the average values (during daylight hours) are 450 W/m² to 320 W/m² for summer and winter, respectively (Figure 6-3d). Since KV62 is located in the central part of KV, it is important to mention that the span between cliffs at the central area of KV is 400 m east–west (Figure 6-1). This gives a greater sun exposure compared to most of the places in the valley throughout the year, despite the fact that the valley is surrounded by tall cliffs which could bias the recorded data (Figure 6-1b). Meteoblue is another available source of information, which provides simulated data from 1985 to date for the Luxor area (meteoblue 2020), which has been used in this study for comparison purposes.

6.5 Methodology

6.5.1 Site Investigation

The rock column above KV42 was instrumented during two field campaigns conducted in April 2018 and April 2019, aiming to record the local weather conditions and the behaviour of the rock mass from a thermo-mechanical perspective. The monitoring system consists of a weather station to record air and rock surface temperature, relative humidity, wind speed and direction, solar radiation and precipitation, as detailed in Table 6-3. Also, a crack meter and an infrared thermographic station (IRT) were deployed in the area (Figure 6-4a) with the IRT data primarily covering the slab 1 surface (Figure 6-4b). The weather station was installed on the western side of the lateral fracture approximately 10 m above the current ground level (Figure 6-4c), whereas the crack meter was oriented horizontally, and installed 6 m above the current ground level. The crack meter was embedded to the western side of the lateral fracture and its free other end was inserted into a small cavity on slab 1. The crack meter recorded the distance between the sides of the lateral fracture, with the definition of opening cycles being those with positive changes in the fracture opening (FO) whilst closing cycles are the negative changes (Figure 6-4d). Since the inherent restrictions in KV to not alter or damage the landscape, none of the rock walls were drilled or sensors forcefully pushed inside cracks. The limitations in accessing the device (i.e. gain permission to work, the COVID-19 pandemic) and connectivity issues resulted in a loss of raw time-series data for rock surface temperature (RST), air temperature (AT) and fracture opening (FO) between April 2018 and May 2021 in the order of hours to months (Figure 5-4e). Data provided by Helio Scientific from KV62 (Figure 6-1b) for AT and RH at KV42 were used to

estimate the missing data, since these parameters were considered not to have many variations across locations within the valley. The wind speed (WS) and wind direction (WD) were estimated with probability density distributions of Kernel type for the hourly data so that mean values per season fall within a statistical 90% confidence interval, using the measured data from KV42.

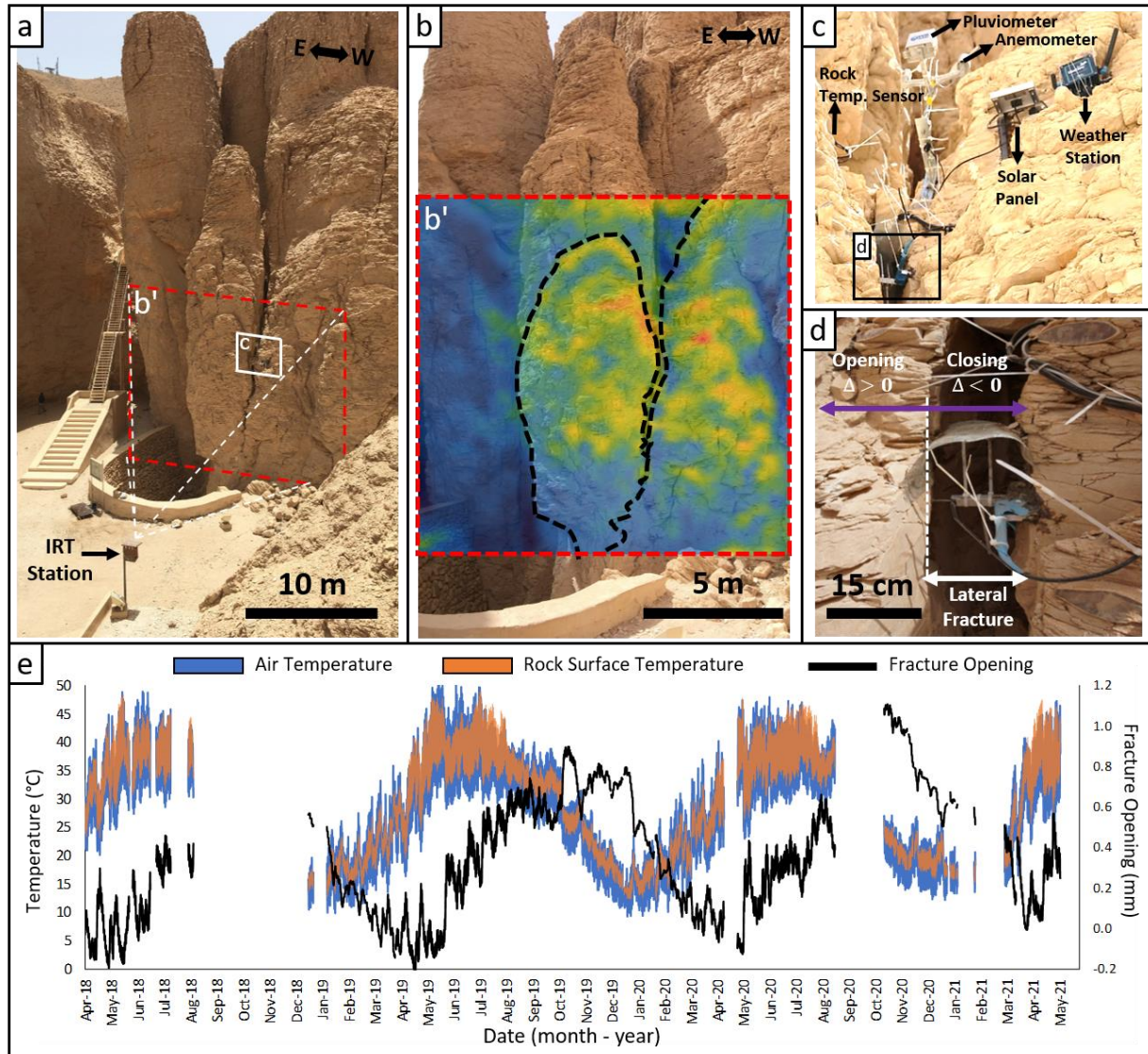


Figure 6-4: Site instrumentation of the rock column above KV42, showing a) panoramic view of the infrared thermographic (IRT) station facing the rock column. The captured sequence is exemplified with the b) infrared image lain over a photograph to illustrate the rock mass portion covered by the IRT sensor. The data acquisition system is deployed within the lateral fracture, where the c) arrangement of environmental sensors and d) crack extensometer (i.e. dendrometer) were attached to the rock mass surface. We defined fracture opening as positive and fracture closing as negative when logging the e) time- series raw data of the fracture cycle, as well as air and rock surface temperature measured by the monitoring system from April 2018 to May 2021. Data for compression of the dendrometer was zeroed after a week (21st April 2018) from starting records.

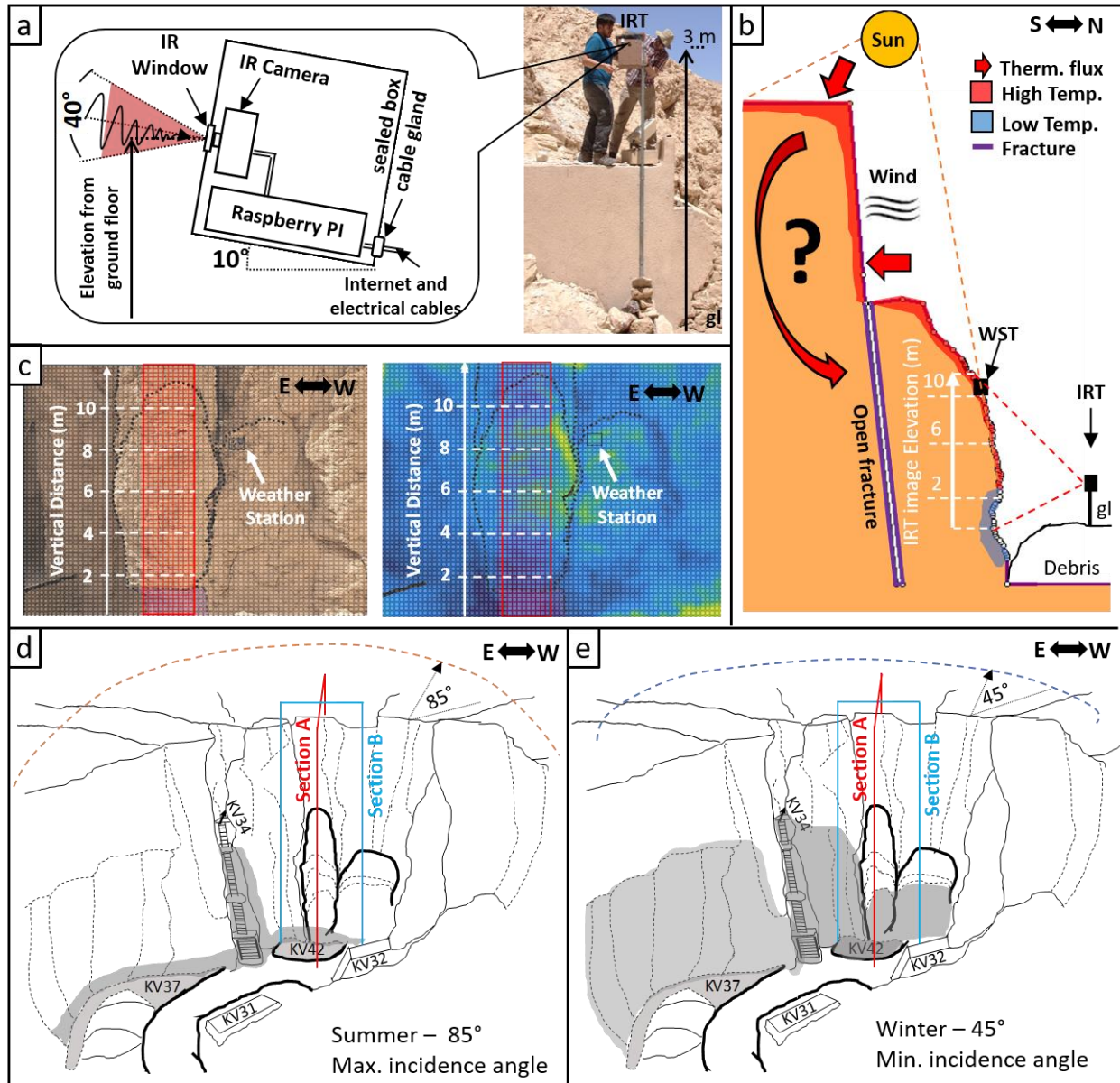
Table 6-3: Description of sensors (model, accuracy, and range of temperature for operation) of WST located above tomb KV42. It must be noted that Ecomatik DC3 has a thermal expansion coefficient of 2×10^{-4} mm/°K. ^aSR raw values are reported within UV–visible range (400–700 nm), and value have been extrapolated to the range of 200–3000 nm (short-wave radiation). ^bAccuracy of the pluviometer is based on bucket capacity. ^cOperational temperature range of WS, WD and PL have been deduced from operational range of wires. Technical information was taken from Libelium (2022) and Ecomatik (2019).

Variable	Variable	Units	Model	Accuracy	Operation T°
Air pressure	AP	Pa	9370-P	± 100 Pa	0–65 °C
Air temperature	AT	°C	9370-P	± 1 °C	0–65 °C
Relative humidity	RH	%	9370-P	< 3%	0–60 °C
Precipitation	PL	mm	WS-3000	0.28 mm ^b	< 70 °C ^c
Solar radiation	SR ^a	W/m ²	SQ-110	± 5%	– 40–70 °C
Wind speed	WS	km/h	WS-3000	2.4 km/h/turn	< 70 °C ^c
Wind direction	WD	°	WS-3000	< 22.5°	< 70 °C ^c
Rock temperature	RT	°C	Pt-1000	± 0.3 °C	– 50–300 °C
Crack aperture	CA	mm	Ecomatik DC3	± 3.3 µm	– 25–70 °C

6.5.2 Defining the Thermal Boundaries of the Rock Column Above KV42

The self-made IRT station uses an infrared camera (FLIR Lepton, LWIR), a protective window (25 mm diameter Germanium anti-reflecting coated disc, 3 mm in thickness), and a microcontroller (Raspberry PI3B +). The components are contained inside a box placed 11 m from the closest point of the rock column and 3 m from the current ground level, oriented NS, with the view angle pointing towards S, and inclined 10° upwards from horizontal (Figure 6-5a). The resulting images cover a vertical distance of 12 m of the rock column from the notch section to above slab 1 (Figure 6-5b). The system determines the maximum and minimum temperature of the image and uses this range to determine a colour scale to display a map of the rock surface temperatures (RST). The system does not record the exact temperature value of each pixel, only the maximum and minimum values and the relationship between subsequent image temperature ranges. The division of this range determines the colour scale for all images which is not linear between images taken at different times, so a relationship cannot be established to determine an absolute temperature value for a scale that represents the temperature range across a year. Only relative comparisons between images can be done. However, the images have played a key role in defining different thermal regions across the rock column. In regular intervals of one hour, the ten central columns of pixels on the rock column are sub-sampled (red squares in Figure 6-5c) to normalize these ten columns by their unique maximum value. This gives the relative RST for a punctual date-time, so it leads to determining the thermal boundaries based on the elevation of those normalized RST exceeding 75% within that hour. For instance, if the maximum RST is 30°C, then given the 75% threshold, only pixels with temperatures above 22.5°C fall within this selection. This delivers a time-series of elevations for the high (> 75% maximum temperature) and low (< 75% maximum temperature) RST values, named as

middle and low regions, respectively. A top region is also defined for RSTs existing at the back cliffs of the area (behind the rock column).



Since the IRT system does not provide numerical values for temperature, but relative differences between pixels, the values of the RSTs for each region are calculated with the local weather

parameters, using the approach from Bentz (2000) for the heat balance. The rock mass exchanges heat with the surrounding environment by four mechanisms: sun radiation incidence (Q_{rad}), long-wave radiation from the rock surface or albedo (Q_{alb}), the convective process of fluids (Q_{conv}) and conduction within the rock mass (Q_{cond}). The general balance is detailed in Equation 6-1, to calculate the total heat transfer under conduction within the rock mass. The calculation of Q_{alb} is detailed in Equation 6-2, with the approximation from Algarni and Nutter (and references therein, 2015) to calculate the temperature of the sky (T_{sky}). The convective heat flux was calculated using Equation 6-3, with a simplified convection coefficient (h) for planar surfaces. The RST is calculated using the RST from the previous interval and the total balance for Q_{cond} of the current time, as detailed in Equation 6-4. The calculations are done iteratively over the time frame of interest.

$$Q_{rad} - Q_{alb} + Q_{conv} = Q_{cond} \quad \text{Equation 6-1}$$

$$Q_{alb} = \sigma \varepsilon_{emi} (RST^4 - T_{sky}^4) \quad \text{Equation 6-2}$$

Where σ : Stefan-Boltzman constant, $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$; ε : rock emissivity, 0.9; RST: rock surface temperature. T_{sky} is the temperature of sky, such as $T_{sky} = 0.037536 * T_{amb}^{1.5} + 0.32 * T_{amb}$ (Algarni and Nutter, 2015).

$$Q_{conv} = h * (AT - RST) \quad \text{Equation 6-3}$$

Where H is the convection coefficient, for wind speed (WS) $\leq 5 \text{ m/s}$, then $h = 5.6 + 4.0 * WS$; otherwise, $h = 7.2 * WS^{0.78}$ (Bentz 2000). AT is air temperature; RST is rock surface temperature.

$$RST_t = RST_{t-1} + \left(2 * \frac{Q_{cond,t}}{k_r} \right) \sqrt{\frac{\alpha * \Delta t}{\pi}} \quad \text{Equation 6-4}$$

Where RST_{t-1} is the rock surface temperature in the previous interval, $^{\circ}\text{K}$, $Q_{cond,t}$ is the heat exchange under conduction at current time, W/m^2 , k_r is the thermal conductivity of rock, W/mK , α is the thermal diffusivity, m^2/s , Δt is the interval of time, for our calculations this was 3600 s (1 h).

The measured RST at the upper part of slab 1 is used for calibration of RST calculated values, so that a time-series can be compared within a similar time-frame to the measured data. Fluctuations in the middle and low regions are related to the natural solar path (i.e., change in maximum incidence angle), which impact the RST during winter and summer differently, as sketched in Figure 6-5d and Figure 6-5e, respectively.

6.5.3 Numerical model set up

A transient, thermo-mechanical finite difference model (FDM) was created using Itasca FLAC®8.0. The model aims at quantifying the mechanical displacement caused by thermal

fluctuations. Two cross sections of the rock column above KV42 were modelled, a SN (A) and an EW (B) section, as shown in Figure 6-5e. Section A extends over 20 m into the cliff and it captures the three slabs, the notch section and the back cliff, whereas section B only focuses on slab 1 and the lateral fracture (Figure 6-6). An open fracture is modelled between the west side of the rock column and back cliff to represent the lateral fracture in section B.

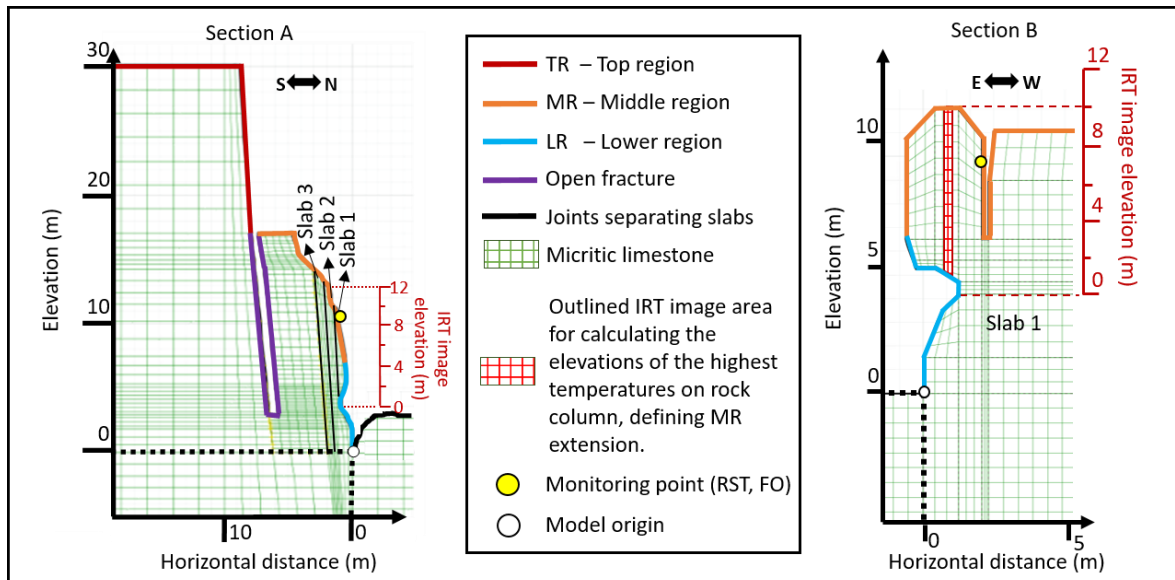


Figure 6-6: Cross sections for numerical modelling, illustrating the extension of thermal regions and the coverage of the IRT images (a vertical axis for IRT is added for illustrative purposes). Section A (SN) represents joints separating slabs and the tall cliff at the back of rock column. Section B (EW) contains only slab 1 and the lateral fracture. The rock type is a micritic limestone. Rock mechanical and thermal properties are listed in Table 5-4.

External forces such as seismic accelerations and water pressure within fractures were neglected because of the low frequency of occurrence (Karakhanyan et al. 2010, Mohamed et al. 2012, Hassan et al. 2017, Paulose 2020). However, thermally active regions (i.e. top, middle and low regions) and the calculated rock surface temperatures (RST) were input into the model accordingly. The vertical origin ($y = 0$) of the model was set at the toe of the slope. The coordinate system origin ($x = 0, y = 0$) to which all measurements are referenced is indicated in Figure 6-6. Section A has vertical boundaries of 30 m south and 15 m north from the origin, whereas section B boundaries are 10 m east and west away from the origin. Vertical boundaries were set with free movement in y-axis and restricted in x-axis. The horizontal boundary (i.e. bottom) was set 15 m below the origin for section A and 10 m for section B, restricting lateral and vertical movements. The upper boundary mimics the topography of the site and has no motion restrictions. The initial rock mass temperature was set 15°C, with all boundaries having a fixed temperature of 15°C except the upper boundary which temperature fluctuates according to numerical functions from the different thermal regions (e.g. top, middle, and low) coded in FLAC®.

Table 6-4: Rock matrix and joint properties used in the thermo-mechanical model in FLAC®. Mechanical constitutive models were input for elastic isotropic and anisotropic (respect to bedding planes) constitutive models. Joints generating slabs (i.e. J1, J2 and J3) were modelled as interfaces with their own mechanical properties. Isotropic thermal properties were adopted for the rock column, whereas the joints were modelled for continuous (i.e. intact rock thermal properties for joints) and discontinuous (i.e. specific thermal properties for joints) scenarios. PA stands for rock property measured parallel to bedding planes, whilst PE is perpendicular.

Property		Mechanical isotropic — thermal continuous	Mechanical isotropic — thermal discontinuous	Mechanical anisotropic — thermal discontinuous	
				PA	PE
Rock matrix	Density (kg/m ³)		2000	2000	2000
	Rock mass elastic modulus (GPa)		6.6	8.7	4.4
	Bulk modulus (GPa)		3.2	5.0	2.0
	Shear modulus (GPa)		2.8	3.6	2.0
	Thermal conductivity (W/mK)		7.5×10^{-1}	7.5×10^{-1}	7.5×10^{-1}
	Heat capacity (J/kgK)		750	750	750
	Expansion coefficient (1/K)		8×10^{-6}	8×10^{-6}	8×10^{-6}
Joints	Normal stiffness (GPa/m)	210		210	
	Shear stiffness (GPa/m)	21		21	
	Cohesion (Pa)	0		0	
	Friction angle (°)	35		35	
	Dilation angle (°)	30		30	
	Thermal conductivity (W/mK)	7.5×10^{-1}		7.5×10^{-3}	
	Heat capacity (J/kgK)	750		750	
	Expansion coefficient (1/K)	8×10^{-6}		8×10^{-7}	

The mechanical constitutive models were defined using an elastic isotropic (ISO) and an elastic anisotropic (ANI) approach, whereas thermal properties were defined as isotropic. However, the joints associated with each slab (i.e. J1, J2, and J3) followed Coulomb shear-strength criteria, allowing inelastic horizontal and vertical displacements along the joints. It is worth mentioning that since section B does not include plastic joints, only elastic deformations are expected as a result of mechanical conditions. Furthermore, the joints' thermal response was tested assuming two scenarios such as intact rock or opened-joint thermal properties, since they play a key role in the heat conduction within the rock mass (Marmoni et al. 2020). The geotechnical and thermal properties for the intact rock and joints are listed in Table 6-4, which were set after several modelling instances which results complied with the convergence criteria and computational time. Major differences are seen in terms of elastic properties, with ANI models being dependent on the orientation of the bedding planes as the anisotropy plane (i.e. 15° dipping towards negative x axis), according to the properties reported by Alcaïno-Olivares et al. (2022). On the other hand, ISO models are set with the average value of both planes of isotropy. Thermal parameters for the thermal discontinuities of joints are set with a thermal conductivity of 2 order of magnitude smaller than the ones tested for intact rock, and to set the infill or lack of confinement for the joints, the expansion coefficient was set one order of magnitude smaller.

The mesh was defined in terms of aspect ratio (i.e. ratio of the zone height to width) smaller than 4:1, which was gradationally finer for those zones close to the slabs and the base of the column. To increase the density of zones, zone multipliers of 2×2 for the rock column and 4×4 between

slabs were applied. For cross-section A, the zone sizes ranged from 0.01 m by 0.02 m at the slab region, to 3.0 m by 3.0 m at the top of the back cliff. On the other hand, cross-section B had a grid size ranging from 0.3 m by 0.1 m at the notch area, to 0.5 m by 0.5 m at the furthest point from the area of interest. To compare the modelled and measured displacements, a control point located in the upper right corner of the column (Figure 6-6) tracked displacements relative to the opposite side located at the cliff in section B which is independent of the zone size since a void was modelled at this location rather than a joint element. Since the grids for sections A and B are set equally for all three models, computational differences are expected in terms of mechanical and thermal calculation steps because these are property-dependent. Nevertheless, the convergence criterion for achieving equilibrium was a stress ratio lower than 10^{-3} on each zone, which indicates the stress acting on a zone in relation to the stress in the other zones in the near vicinity do not differ by more than the stress ratio to ensure numerical equilibrium is achieved under minimal unbalanced forces (Itasca Consulting Group 2019). For this reason, under thermo-mechanical conditions, the model was forced to provide an elastic solution only after running 10 mechanical steps for each thermal step. The results were queried linearly (i.e. several nodes across a line) and nodal-wise (i.e. specific points between slabs and at the monitoring point) as time-series, covering the monitored period from April 2018 to May 2021.

6.6 Conceptualisation of Thermo-Mechanical Conditions Acting in the Rock Column Above KV42

6.6.1 Measured Environmental Data

The data collected for both air temperature (AT) and rock surface temperature (RST) fluctuate, from a minimum of 10°C during the cooler months (December–February) to a maximum of nearly 50°C during the warmest months (June–August), with an average daily fluctuation of 10–15°C between the minimum and maximum temperatures, as shown in Figure 6-4e. The average air temperature for the recorded period is 27°C, which is like recordings at Luxor Airport and KV62, however, differences are seen in terms of maximum and minimum values for KV42, as tabulated in Table 6-5. These values can be linked to the location of the stations (i.e. Luxor Airport is in a flat open area, whereas KV42 and KV62 are inside a valley).

The fracture opening (FO) data oscillates yearly with the seasons, like the RST, suggesting a contribution of the RST to the FO values as shown in Figure 6-4e. However, the data show a shift in the dates between maximum RST and maximum FO of typically 1–2 weeks for short-term peak values (i.e. within a month) and up to a maximum of 14 weeks for yearly trends (i.e. along all seasons). The maximum FO values are reached in November and range from 0.6 to 1.0 mm,

whilst the minimum values range from 0.0 to -0.3 mm in April and May. FO-measured values comprise an increasing trend of a maximum of 0.2 mm on an annual basis, whereas measured RST values do not increase significantly in overall. This ongoing change indicates that the FO increased during the observed period (April 2018 to May 2021). However, the gypsum marks placed on the outer surface only tell if the fracture moves on the cliff surface. It does not provide information on fracture growth below the marker or growth inside the rock mass. It is important to mention that other common driving mechanisms for continued fracture growth and opening, such as regional earthquakes or rain, did not occur during the observation period.

The gaps in the time-series of measured data were filled with estimated values. Figure 6-7 shows the finalized time-series, identifying measured and estimated data, and Table 6-5 summarizes the characteristic values by season for the complete time-series. The time-series of AT (Figure 6-7a) shows an average difference between maximum and minimum temperatures of 10°C, which increases during the summer months (June–August) to 18°C; whereas RH values (Figure 6-7b) show an opposite trend for the time-series with local maximum values of 65% measured in the winter months (December–February), and minimum of 5–10% in summer. The SR maximum values (Figure 6-7c) have a sharp change during autumn (i.e. average of 260 W/m² during September to November) and spring (i.e. average of 45 W/m² during March to May) which is a consequence of the solar inclination in combination with the morphology of the area (Figure 6-1b and Figure 6-5d, e). Wind speed and wind direction time-series are introduced in Figure 6-7d as average hourly values per season over a day. Wind speeds of 0.5 km/h are measured between 4 and 8 am in all seasons, whilst increases of up to 1.0 km/h (winter) and 2.5 km/h (summer) at about 8 pm are observed, although the slope of the curve between 8 am and 8 pm is steeper (2.0 km/h /12 h) in summer than in winter (0.5 km/h /12 h). Amongst all variables, the wind direction is the most consistent amongst seasons, with day-time (i.e. 7 am to 18 pm) orientations towards north (plateau breeze) and night-time (i.e. 18 pm to 7 am) to south (valley breeze). This variation between day and night is related to the day- time heating and night-time cooling of the slopes of the Theban Mountains, leading to a switch in the air pressure differences and triggering the wind orientation change by 180° in the KV. Data of AT, RH and SR of the Luxor airport, KV62, and meteoblue were compared for the 2018–2021 period (Figure 5-7e), showing Pearson-type correlation values higher than 0.8 for the data measured above the entrance of KV42.

Table 6-5: Correlation values for air temperature (AT), relative humidity (RH) and sun radiation (SR) between the data from weather stations at KV42 and KV62. Linear relations have been defined for AT and RH, whilst an exponential correlation maximizes the coefficient of correlation (R^2) for SR. *win* Winter, *spr* spring, *sum* summer, *aut* autumn. ^aThe term slope stands for the multiplier of the variable in the exponent for exponential relations. ^bThe intersection of an exponential relation is the multiplier of the exponential function.

	AT — Air temperature °C				RH — Relative humidity %				SR — Solar radiation W/m²				WS — Wind speed km/hr				WD — Wind direction
Regression type	Linear				Linear				Exponential				Probability density distribution type: Kernel *** Mean values determined within a confidence interval of 90%				Similar to WST62, guided by changes in temperature between plateau and valley along the day. Night: South; Day: North
R²	0.94				0.82				0.73								
Slope	1.01				1.24				0.01 ^a								
Intersection	-0.44				-10.16				1.66 ^b								
Season	win	spr	sum	aut	win	spr	sum	aut	win	spr	sum	aut	win	spr	sum	aut	See Figure 5-7d for the change in trends along a day at different seasons.
Mean	16.9	28.3	36.1	28.5	38.1	11.9	5.3	21.3	15	70	80	35	0.61	0.81	1.28	0.70	
Maximum*	20.9	33.2	42.8	33.3	51.4	23.6	13.4	34.2	45	195	260	95	2.08	2.59	4.04	2.45	
Minimum	13.0	22.1	30.9	23.5	24.6	5.0	--	10.6	--	--	--	--	0.10	0.12	0.09	0.12	
Std. Dev.	3.4	7.1	4.2	6.0	11.2	11.9	6.8	12.6	20	75	90	40	0.75	0.89	1.30	0.8	

Table 6-6: Characteristic values for rock surface temperature (RST) and fracture opening (FO). Measured (raw) and estimated values from April 2018 to May 2021, which are summarized by season. ^aMaximum and minimum refer to the extreme single value within the season. *win* Winter, *spr* spring, *sum* summer, *aut* autumn.

	RST — Rock surface temperature °C								FO — Fracture opening mm							
	Measured				Estimated				Measured				Estimated			
Season	win	spr	sum	aut	win	spr	sum	aut	win	spr	sum	aut	win	spr	sum	aut
Mean	18	29.4	37.2	28.7	18.2	29.2	36.9	29.4	0.5	0.07	0.32	0.72	0.6	0.07	0.31	0.90
Maximum ^a	24.4	48.3	48.8	40.9	29.5	48.3	48.8	43.4	0.99	0.57	0.69	1.1	1.0	0.44	0.81	1.1
Minimum ^b	12	14.7	29.3	17.5	8.4	14.7	27.4	15.7	0.06	-0.23	-0.1	0.35	0.16	-0.14	-0.09	0.57
Std. Dev.	2.3	6.5	2.8	5.3	2.9	6.4	3.0	5.4	0.23	0.15	0.17	0.19	0.20	0.15	0.22	0.12

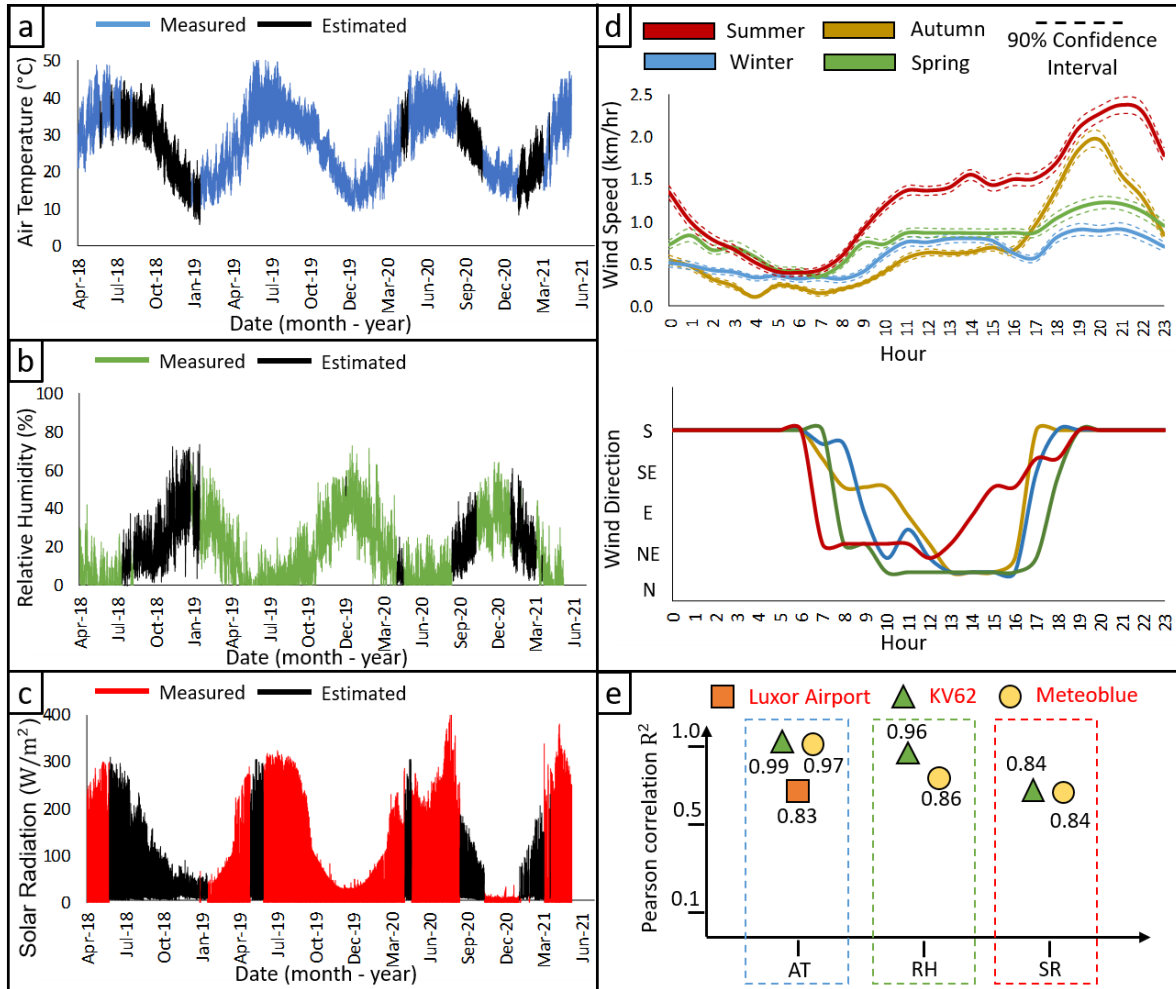


Figure 6-7: Time-series of environmental data measured above KV42 from April 2018 to May 2021. Estimated values were derived using probability distribution functions and data measured at KV 62 (from Helio Scientific group, data restricted under copyright). a) Shows the air temperature, b) the relative humidity, c) the sun radiation, d) the wind speed and direction categorized by season, showing mean values within a 90% confidence interval, and e) the Pearson correlation values for air temperature, relative humidity and sun radiation of KV42, when compared to other data sources (Luxor airport, KV62, and meteoblue). A summary of characteristic values is given in Table 6-5.

6.6.2 Measured Data of Thermo-Mechanical Response

The thermo-mechanical response of the rock column is reported in terms of rock surface temperature (RST) and fracture opening (FO), which are both measured on the western edge of slab 1 as shown in Figure 6-4 and Figure 6-6. Data were acquired with the same monitoring system used for the environmental data from KV42. Hence, missing data are seen in the same dates as those for the measured environmental data. Readings gathered for the 2018–2021 period are introduced in Figure 6-8, which includes both raw and estimated values with their characteristic values for RST and FO tabulated by season in Table 6-6.

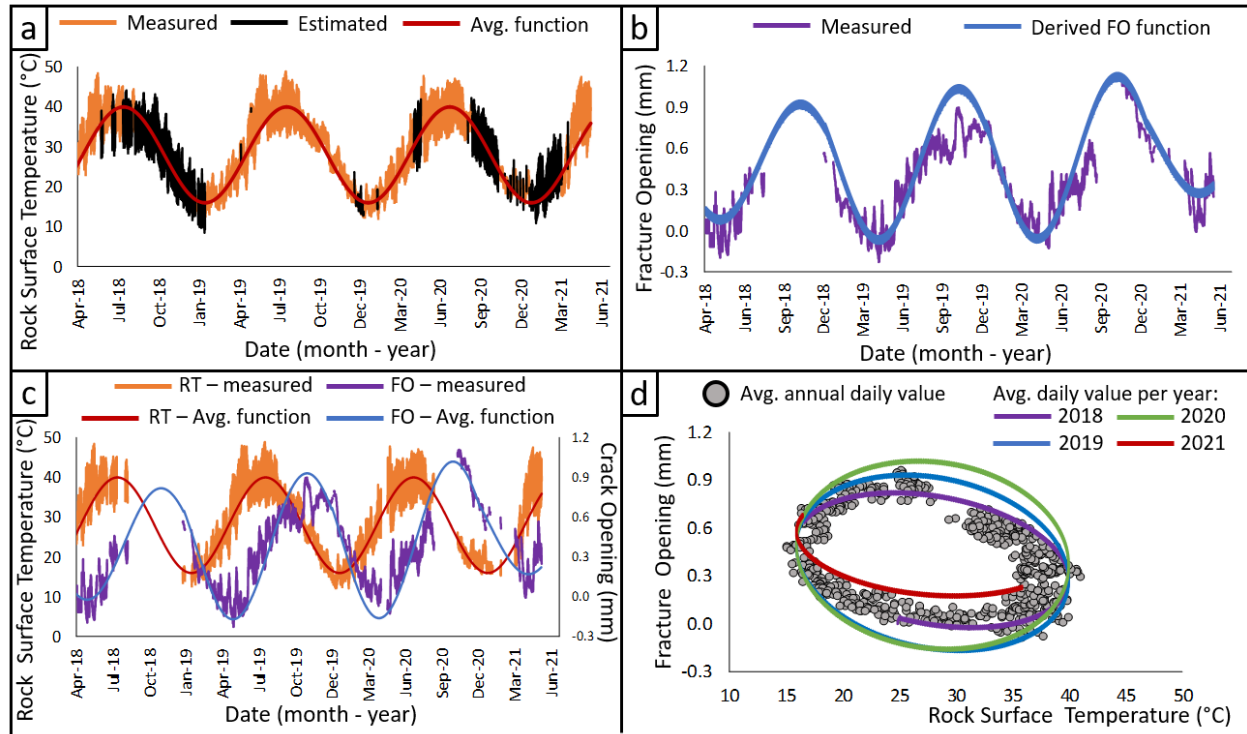


Figure 6-8: Time-series of thermo-mechanical rock mass behaviour measured above KV42, from April 2018 to May 2021. Missing data were filled for a) rock surface temperature (RST) time-series with estimated data from historical air-rock temperature correlations which fitted a sinusoidal function (average function); likewise, a sinusoidal function was derived for b) fracture opening (FO) time-series, compounded by seasonal (year) and daily (by hour) functions (derived FO function). Integrated data of c) RST (left axis) and FO (right axis) show measured data and fitted trends (average functions), which can be divided into years to plot d) thermo-mechanical cycles for FO with respect to RST for averaged daily values from both the fitted trends (average functions) and measured data.

Time-series of RST (Figure 6-8a) were completed using a linear correlation between air temperature and RST for the known values, with a correlation coefficient (R^2) of 0.95. To avoid biasing the FO time-series, no environmental parameter nor RST values were used to estimate the FO values. Nevertheless, a sinusoidal function was adjusted ($R^2 = 0.8$) to the raw data following similar daily fluctuations per season, averaging the sudden changes but having an incremental trend between different years as experienced by slab 1 (S1) (Figure 6-8b). Hence, average functions for RST and FO can be compared throughout the monitoring period (Figure 5-8c) and showed an offset of 3.5 months between peak values. For instance, the hottest RST occurs in July, whereas the largest FO develops in October. The measured and estimated data are presented in Table 5-6. The cycles of FO related to RST fluctuations are highlighted in Figure 5-8d. Data from average functions were grouped by year from 2018 to 2021, whilst the measured data are plotted for daily averages for the entire monitoring period. It was observed that every year, for variations of the RST within $\Delta 20^\circ\text{C}$ the rock column experienced FO of about $\Delta 0.4$ mm. Yearly maximum values of FO increase per year, however, the RST maximum values are constant and lower than

38°C. For the measured data, the wider variability in FO takes place for RST values between 35 and 40°C, whilst in the lowest RST range from 15 to 20°C the measured data match the yearly average functions of RST and FO. Calculations based on the cyclic plot shown in Figure 5-8d show that the average thermo-mechanical response of the rock column occurring during a year, by using the average fracture opening between years and divided by the range of temperature. This value is 0.05 mm/°C for the 2018–2021 monitored period.

6.6.3 Heat Transfer Processes on the Rock Column

The rock mass temperatures of the outer face of slab 1 were captured with the infrared thermographic system (IRT) from April 2019 to April 2020, and the acquired images aided in defining the thermal boundaries extension within the rock column above KV42. A threshold of 75% of maximum RST was set to determine the border between medium and low RST, as shown in Figure 6-9a. The elevation refers to the vertical distance within the picture which is projected on the rock column in Figure 6-6. Each scenario shows the average RST value from this elevation upwards, and the plot highlights when the average RST is at least 75% of the maximum temperature value. The results display the fluctuations in day and night RST, with the 2 m elevation varying from 30 to 70% of the maximum RST, whereas the 10 m elevation only ranges between 10 and 40%. The region from 6 m height had on average values above 75%, however, it ranges from 50% to 95% of maximum RST. Therefore, the 75% threshold was queried over a year differentiating between day time (6 am to 18 pm) and night time (18 pm to 6 am), which is introduced in Figure 6-9b.

The longest extension (i.e. 3.4 m from the bottom of the picture, which is 8.6 m from the top) takes place during June and July (i.e. hottest months) for the day time, yet it also spans the largest height difference (1.6 m) when compared to the night time extension for the same months. During January and February (i.e. coldest months), this span shortens to 0.4 m (i.e. 4.6 m during day time and 4.2 m during night time). As introduced in Figure 6-6, the region above 75% of the maximum RST on the rock column is named the middle region (MR) whereas the region below is named the low region (LR), and their dynamic extension is sketched in Figure 6-9c for the cross-section B. The change in the size of the MR and LR is small for the coldest months. The lateral fracture tip lies solely in the LR. During the hottest months the day time extension of MR reaches close to the lateral fracture tip (30 cm above), whereas it moves upwards in the night time along with the LR, leading to a cycle of heating and cooling of the lateral fracture tip. It is worth reminding that a third thermal boundary, named the top region (TR), in the back cliff, which is not captured by the IRT system (Figure 6-6), is used in the numerical model for cross-section A only.

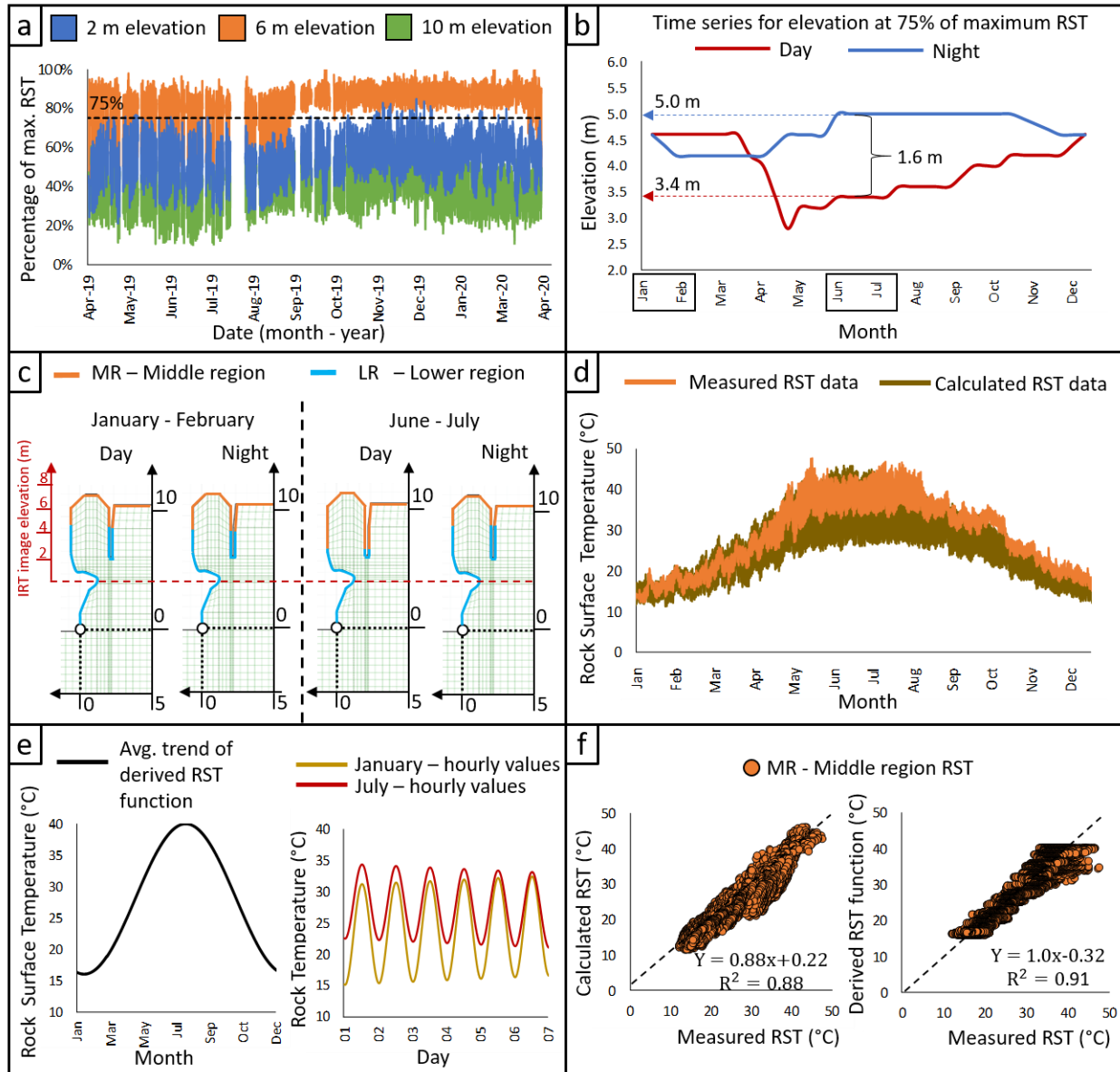


Figure 6-9: Definition of the extension of the thermal regions, using a) the time-series of the percentage of maximum rock surface temperature (RST) surveyed by the IRT system at different elevations (2 m, 6 m and 10 m, based on IRT reference elevation). The middle region (MR) is defined as b) the monthly average elevation for 75% of maximum RT for the day and night shifts. Therefore, the MR extension varies along the year, geometrically such as c) the day-night thermal boundary changes between winter (January–February) and summer (June–July). The RT values of each thermal region are calculated on the external boundary using the model of Bentz (2000) and validated by comparing d) the time-series for 12 months of calculated RST to daily average of measured RST data, to construct e) derived RST functions, using annual and daily sinusoidal trends (e.g. January and July). Both data sets are presented in f) scatter plots of calculated and derived RST against measured RST, including linear relationships. Note: functions for top, middle and lower region are presented in APPENDIX B.

The RST values for the LR, MR, and TR regions were calculated with the thermal balance proposed by Bentz (2000), using a 12 months' time-series of the environmental data collected at the site by hourly averaging the data collected from April 2018 to May 2021. To calibrate the thermal properties, RST values were calculated and compared to the measured RST at the point

where the rock temperature and crack meter sensor are installed (i.e. 6 m above the current ground level within the lateral fracture), as shown in Figure 6-9d. Measured and calculated values for RST were correlated linearly, delivering a correlation factor (R^2) of 0.8. During the hottest season (i.e. June to July), the calculated RST data had 7°C lower values than the measured data for the same day and hour, which relates to the limitations of Bentz's model (i.e. no sharp changes in RST since it uses previous data for calculating current RST) and the interaction of the sensor with the ambient (i.e. localized shading effects). Nevertheless, in longer extensions such as MR, this approach provides trends and average values for deriving average functions. For instance, the trend of the sinusoidal thermal function of the MR was derived from calculated RST data and coupled with hourly fluctuations (unique per month), to define the annual MR time-series of RST (Figure 6-9e). As shown in Figure 5-9f, when correlating calculated RST to measured RST the R^2 is 0.88, however, when using the derived RST function, the R^2 improves to 0.91. A similar methodology was applied to the TR and LR, and their derived functions are compared to the calculated RST with R^2 of 0.81 for both. For the TR and LR, specific conditions were analyzed (i.e. sun radiation, wind speed, etc.) because of the geometry of the cliffs and rock column. The RST functions are displayed in APPENDIX B, and these form the basis for the thermal inputs of the numerical model.

6.7 Thermo-Mechanical numerical model Results

The results from numerical modelling were extracted in terms of RST distribution and displacement for elastic isotropic (ISO) and anisotropic (ANI) constitutive models, modelled in sections A and B. A series of linear and nodal surveys were used to study the thermo-mechanical behaviour of the rock column. The locations of these surveys are given in Figure 6-10a, which shows three horizontal and two vertical surveys to compare the rock slab behaviour with the more intact rock mass behaviour deeper in the cliff. After the numerical model reached mechanical elastic equilibrium (i.e., stress ratio lower than 0.001), the data were extracted either as a complete time-series (i.e., from April 2018 to May 2021) or the same days of each year were averaged to minimise erratic trends, named as daily average time-series.

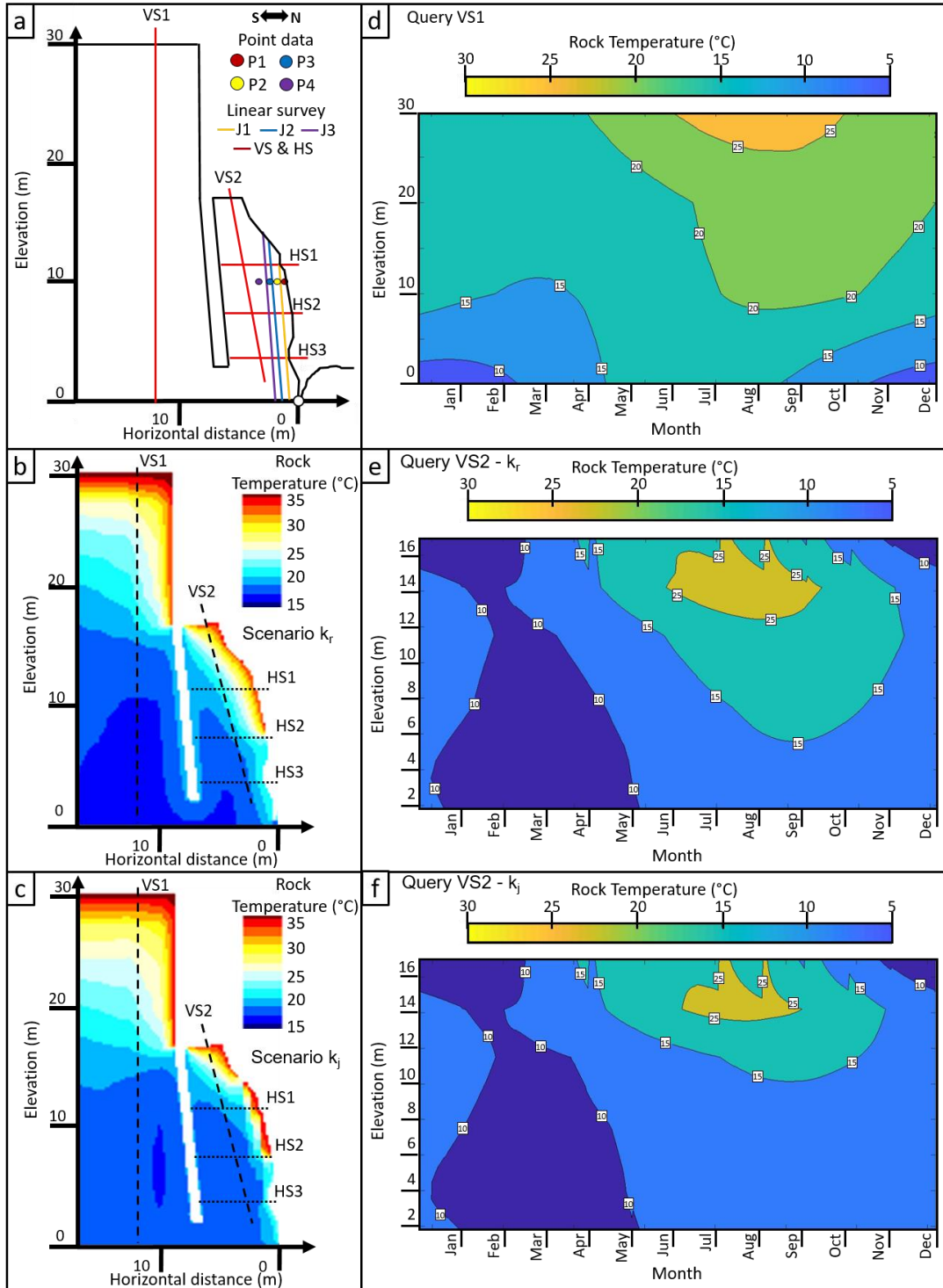


Figure 6-10: Numerical simulation results of rock temperature distribution for cross-section A, recorded at a) surveyed points (P#) and lines (Vertical Survey, VS#, and Horizontal Survey, HS#). Overall results are sketched as colour maps for both b) a model with closed joints (J#) of intact rock thermal conductivity (k_r), and c) a model with open joints of different thermal conductivities (k_j) compared to intact rock (Table 6-4). Linear results are shown as colour maps of yearly average time-series for d) vertical survey 1 (VS1), e) vertical survey 2 (VS2) for the model with the same thermal properties (k_r) and f) with different thermal properties for opened joints (k_j) and intact rock.

6.7.1 Rock Temperature Distribution

The rock temperature (RT) circulation is a result not only of the dynamic interaction of the thermal boundaries but also the effect of the joints associated with each slab (i.e. J1, J2 and J3). Even though the overall model was defined as thermally isotropic, the joint thermal conductivity was set for two scenarios, (1) joints with intact rock parameters (k_r , 0.75 W/mK) and (2) joints that represent open-joint thermal conductivity (k_j , 7.5×10^{-3} W/mK). Data queried on the rock column aimed to capture the heat flow propagation across it from the various survey locations shown in Figure 6-10a.

Graphic comparisons between both scenarios for a random day in July 2020 are shown under intact rock (Figure 6-10b) and open-joint (Figure 6-10c) conditions, where major changes in the rock temperature are seen in the outer face of the rock column. For instance, the intact rock scenario shows a continuous heat propagation inward from the rock surface which is driven by the RST from the middle region's thermal boundary, whereas the open-joint scenario displays a heat accumulation between J1 and the outer rock face of the cliff. The average RTs of slab 1 are 25°C and 30°C for intact rock and open-joint, respectively. At the back cliffs (VS1), the RT data is not affected by the thermal properties of the joints, so VS1 remained similar in both cases. There is a yearly fluctuation driven by the top region's thermal boundary only, as shown in the colour map of Figure 6-10d. Average RTs higher than 25 °C are expected to take place at depths no greater than 4 m between June and October, whilst the section up to 10 m fluctuates between 15°C and 20°C in the back cliff.

During the coldest months (i.e. January and February), VS1 shows RTs of 10°C for elevations up to 5 m, with maximum RTs between 15°C and 20°C for regions above 5 m. However, behind J3, the VS2 shows that the intact rock scenario causes smaller propagation and a shorter duration of the high RST. Figure 6-10e and f display the daily average time-series (i.e. averaging the same day of each year) of VS2 for the intact rock and open-joint scenarios, respectively. RT of 20°C reaches an elevation of 6 m at the start of September for the open-joint scenario, and only 10 m for the intact rock scenario at the same period. The intensity of the heat gradient is seen in the depth of penetration of hotter temperatures, such as the 20°C isolines from June for the intact rock scenario, which differs from the same isolines for the open-joint model. In contrast to the opened-joint model, a big change in heat gradient happens from July. It is worth noting that both models were set with the same thermal boundary and functions. For the winter months (i.e. December to February) the RT remained similar in both scenarios.

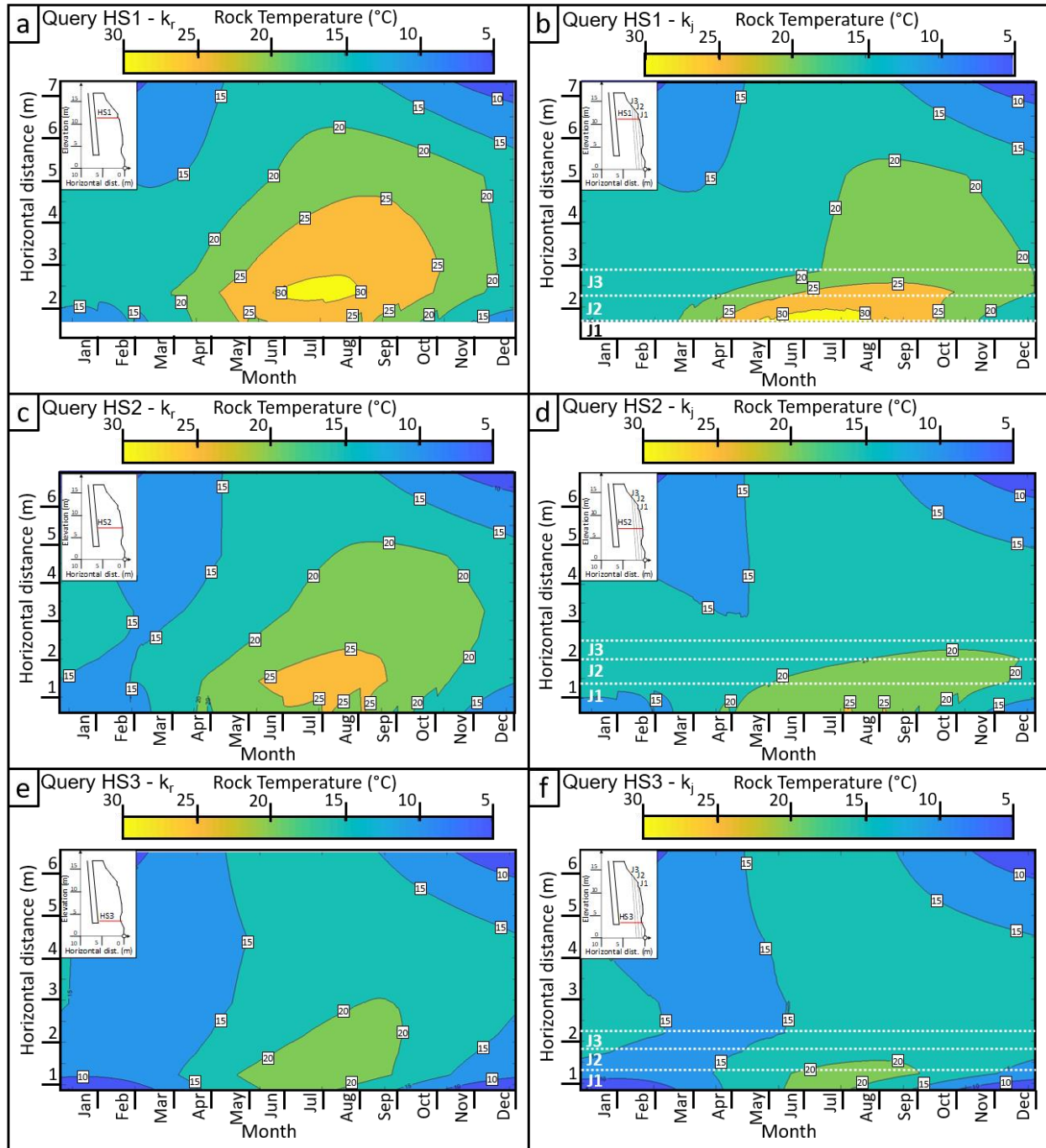


Figure 6-11: Rock temperature data simulated for cross-section A, recorded across horizontal surveys (HS#) for a 12-month period. Location of surveys is referred to Figure 6-10a. Joints (J#) are set with thermal properties similar to the rock intact properties (Table 6-4), such as in a), c) and e) to show the yearly average time-series for the continuity of temperature distribution across the rock column. Specific joint thermal properties (Table 6-4) are set for b), d) and f) models to illustrate the impact of the joints on the thermal conduction within the rock mass.

Horizontal surveys (Figure 6-10a) at different elevations in the rock column were conducted to illustrate the fluctuation in RT at specific features of the rock column, such as above slab 1 (HS1), the transition between the middle and low region (HS2) and the notch section (HS3). The results

are introduced in Figure 6-11 for the intact rock and open-joint scenarios, as colour maps with the y-axis as the horizontal distance from the model origin and dotted white lines on the map illustrate the location of the joints. HS1 does not intersect J1, so null values are plotted for J1 in Figure 6-11a, b, as a blank space. For the intact rock scenario (Figure 6-11a), the RT above 30°C occurs at a horizontal distance of 2.5 m in July–August, with an extension to 4.5 m for an RT above 25°C between May and August is at 2.3 m for intact rock (Figure 6-11c) and this distance decreases to 0.2 m (i.e. limited by J1) when the open-joint scenario is implemented (Figure 6-11d). Moreover, the RTs above 20°C are limited by J3 (2.5 m), although spanning a similar time frame compared to the intact rock scenario. At the notch section (i.e. HS3, Figure 6-11e, f), a maximum RT of 20°C is reached between June and September for the intact rock scenario, whereas for the open-joint scenario, RT of 20°C is limited within J2 (1.8 m) between June and September.

The slab 1 rock temperature distributions were modelled in cross-section B, including the adjacent portion of the rock mass at the western side, so that the lateral fracture could be explicitly represented as an open fracture (Figure 6-12a). It is worth noting that the joints associated with the slabs strike in the same direction as the cross-section B, so that they only influence the behaviour of slab 1 in the out-of-plane section (following section A orientation). This means that no shear or normal displacements from joints are expected for section B. Data were extracted as linear surveys (VS3, HS4). The control point FO captures the behaviour of the rock column at the installed crack meter's location, and its results are analyzed and compared in Section 6.8.1. The RT distribution is shown in Figure 6-12b, c for conditions at 13 pm (i.e. at the hottest hour) of a day in winter and summer, respectively.

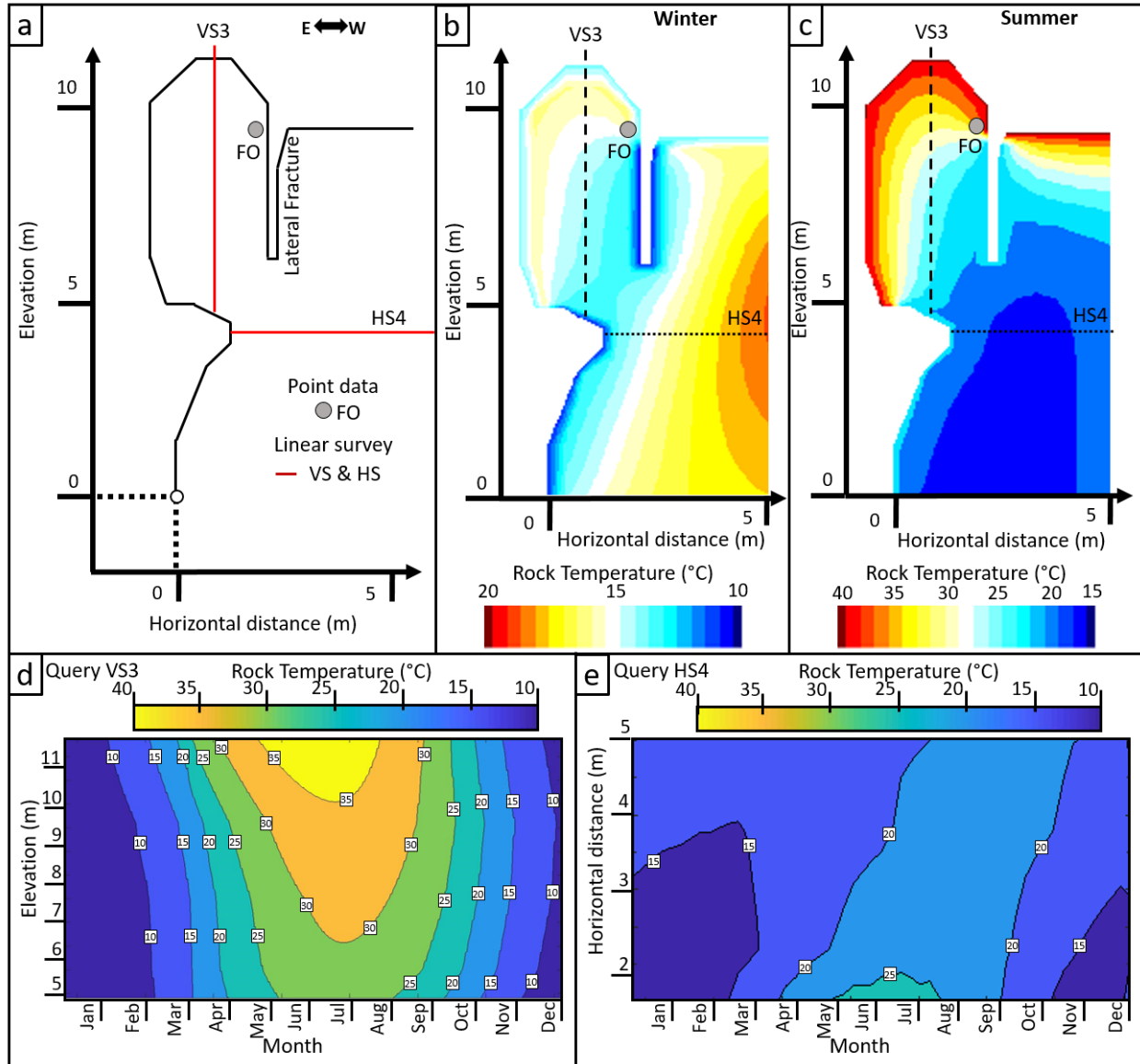


Figure 6-12: Numerical simulation results of rock temperature distribution for cross section B (slab 1), recorded at a) surveyed point (FO) and lines (Vertical Survey, VS3, and Horizontal Survey, HS4). Sketch of temperature distribution across slab 1 for a given thermal fluctuation in b) winter and c) summer. The daily average time-series are plotted as colour map for both linear surveys d) VS3 and e) HS4.

Since the initial RT was set to 15°C, and taking into account that the middle region fluctuates above 15 °C whilst the lower region fluctuates below 15°C during the coldest month, the RT for the rock mass changed across the column. For instance, the model shows an average temperature contrast between the eastern and western edges of the rock column of 5°C for winter and 15°C for summer. Hence, the lateral fracture is at the coldest edge of the modelled slab, with the seasonal average RT ranging between 15°C (winter) and 23°C (summer). The notch section is also a cool area with RTs between 10°C to 20°C in both seasons. The central vertical axis (VS3) of the rock column was

queried, and the results are displayed as daily average time-series colour maps in Figure 6-12. RTs above 40°C are captured for summer months (i.e. June to August), reaching a maximum in July (Figure 6-12d). RTs colder than 30 °C persist throughout the year at an elevation below 6.5 m, close to the lateral fracture tip. RT decrease starting in July, reaching values below 20°C by the middle of November. Similarly, the notch section (HS4, Figure 6-12e) shows RT slightly below 10°C for the shallower layers (i.e. 1.5 to 2.0 m from the model origin) during the winter (i.e. December to February), increasing above 10°C around 2 m from the model origin. RT values along HS4 of 20°C are obtained in summer months only, with an extension larger than 7 m into the rock column. Beyond 3 m horizontal penetration, the RT values range between 15°C and 20°C. Therefore, the largest RT fluctuations and clear occur in slab 1 considering thermal intact rock conditions. This is also seen in cross-section A when modelling the three slabs, which showed the effect of open-joints on the distribution of RT within the rock mass and the influence of slab 1.

6.7.2 Transient Joint Displacement

Joint displacements are reported from linear surveys between slabs, along the modelled interface elements that represent the joints labelled J1, J2 and J3 in Figure 6-10a. The colour maps of Figure 6-13 display the results in millimeters (mm) of displacement (Δd) for the elastic isotropic (ISO) and elastic anisotropic (ANI) constitutive models. The displacement is the change in length of the vector from the origin of the cross-section, extracted as horizontal (Δx) and vertical (Δy) displacement differences. To combine both displacements, a total 2D displacement was calculated as the length of the vector between Δx and Δy (i.e. total displacement, $\Delta d = \sqrt{(\Delta x)^2 + (\Delta y)^2}$). The data are presented in Figure 6-13 as a time-series from April 2018 to May 2021, with the y-axis following the joint trace in the vertical direction. Overall, the results show that the ISO models have larger displacements than ANI models, with average maximum values amongst all joints of 2.3 mm and 1.0 mm, respectively.

Furthermore, the incremental trend of displacement for all joints suggests an opening of the joints, aligning with the plastic properties input for the joint elements, and regardless of which constitutive model and joint thermal scenario (intact or open) were used for the rock mass. The ISO model delivers displacements larger than 0.5 mm for the first months of the simulation (i.e. April 2018 to January 2019) at elevations of 5 m for J1 (Figure 6-13a), 6 m for J2 (Figure 6-13b) and 10 m for J3 (Figure 6-13c). J1 reaches the maximum displacement value of 3.5 mm at the end of the simulation at 7 m, whereas J3's maximum displacement of 1 mm reached 13 m elevation during the last months of the simulation (i.e. from January 2020). Inelastic deformations as seen for J1 and J2 were expected due to the plastic behaviour set for the joints only. The isolines of

displacement show a change throughout the simulated period, as well as, for J3 the isolines change with the elevation showing progressive displacement which is either linearly increasing (e.g. J1 and J2 for ISO, and J1 for ANI) or cyclically increasing (e.g. J3 for ISO, and J2, J3 for ANI). The results for ANI models show that J1 (Figure 6-13d) had a maximum value of 1.4 mm during the last 3 months of the simulation (i.e. from March 2021), and it reached above 0.5 mm from January 2019 at an elevation of 7 m. Similarly, J2 (Figure 6-13e) reached displacements larger than 0.5 mm at 8 m of elevation in October 2018, whereas J3 (Figure 6-13f) reached it at 11 m in December 2018. Progressive displacements were also observed for the ANI model, with lower values than those for ISO model. J1 had the largest displacement for ISO (avg. 2 mm) and ANI (avg. 0.8 mm) models throughout the simulation time period.

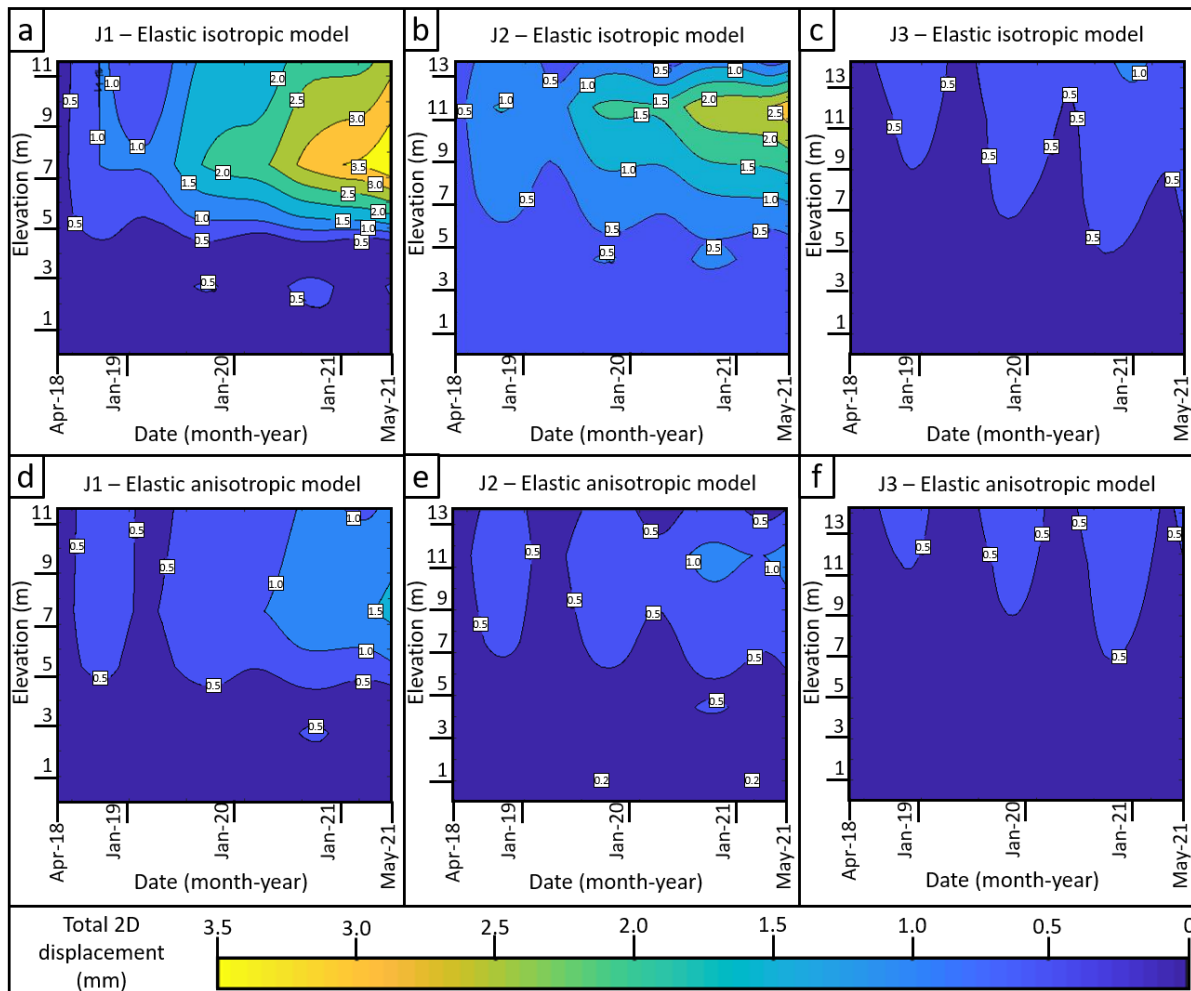


Figure 6-13: Time-series of thermo-mechanical results for total 2D displacement in mm, modelled for the same monitored period in rock column KV42 (April 2018 to May 2021). Total displacements were calculated as the length of the vector formed by horizontal and vertical displacements. Data are recorded as linear surveys across the joint separating slabs (i.e. J#). Mechanical constitutive model was set as elastic isotropic for a) J1, b) J2 and c) J3; as well as elastic anisotropic as shown in d), e) and f), respectively.

6.7.3 Numerical Thermo-Mechanical Behaviour of the Slabs on the Rock Column

The transient behaviour of the slabs (i.e. S1, S2 and S3) was studied with the information extracted from four control points defined in cross-section A, at a similar elevation as the crack meter installed in the lateral fracture and between HS1 and HS2 (Figure 6-10a). Each control point was set to a certain feature in the model, such as P1 for slab 1, P2 for slab 2, P3 for slab 3 and P4 for the intact portion of the rock column behind slab 3. The information was collected from the model for horizontal and vertical displacements, as well as the simulated rock temperature (RT) between April 2018 and May 2021. Positive horizontal displacements are referred to the movement towards the north or away from the cliff face, whilst negative vertical displacements describe a downward movement.

The results are introduced in Figure 6-14 as thermo-mechanical cycles between horizontal displacement and RT (Figure 6-14, a–d) and vertical displacement and RT (Figure 6-14, e–h), for elastic isotropic (ISO) and anisotropic (ANI) mechanical constitutive models. The largest difference between the constitutive model results is seen for P1 (Figure 6-14a), where the ISO scenario gave an increment in horizontal displacement of $\Delta 1$ mm for a full cycle of RT (i.e. from 15 to 35°C and back to 15°C) reaching a maximum of 3.5 mm at the end of the simulation. This contrasts with the ANI model which resulted in a cyclic horizontal displacement of $\Delta 0.4$ mm for each cycle with a maximum horizontal displacement of 1.4 mm at the end of the modelling period. For P2 (Figure 6-14b), the horizontal displacements after each cycle were $\Delta 0.75$ mm (ISO) and $\Delta 0.25$ mm (ANI), with a final extension of 2.5 mm and 0.8 mm at the end of the modelling, respectively. However, for the horizontal displacement P3 (Figure 6-14c), the yearly trend for first, second and third cycles increased from $\Delta 0.2$ mm, to $\Delta 0.05$ mm and finally to $\Delta 0.04$ mm for the ISO models, respectively.

For the ANI model results the cyclic changes were $\Delta 0.1$ mm, $\Delta 0.06$ mm and $\Delta 0.03$ mm, for the first, second and third cycles, respectively. The maximum horizontal displacement was 0.32 mm for the ISO model and 0.22 mm for the ANI model. It is worth noting that the RT ranges for slab 3 were from 15°C to 25°C, smaller than the RT range for slab 1 and slab 2, as shown in Figure 6-11b, d. Finally, P4, (Figure 6-14d) had a maximum horizontal displacement of 0.48 mm (ISO) and 0.20 mm (ANI), for a range of RT between 13°C and 17°C. Horizontal displacements for all points and constitutive models were positive (i.e. moving towards the North) because the joint elements were modelled as plastic so progressive displacement is allowed with no failure of the surrounding rock mass.

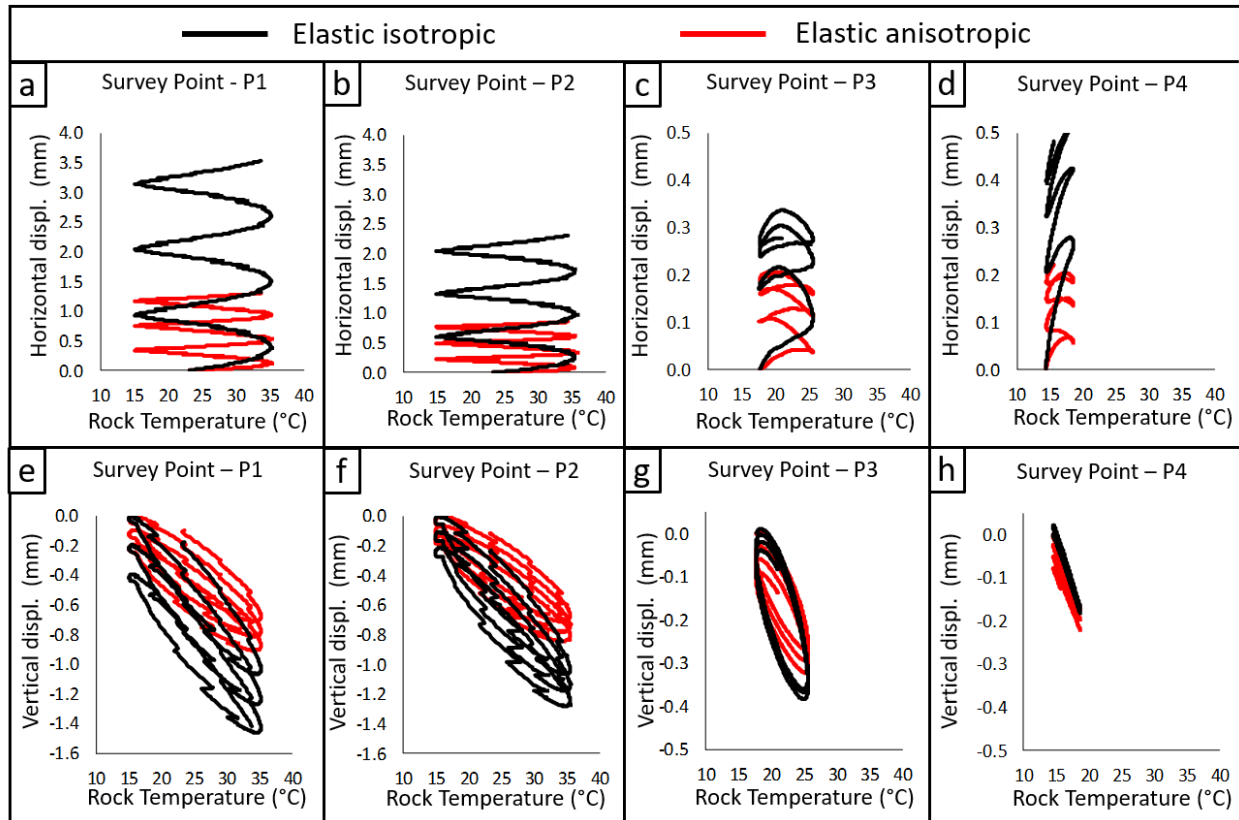


Figure 6-14: Thermo-mechanical behaviour of rock slabs (i.e. Slab 1, 2 and 3) and rock column recorded as total displacement of surveyed points (P#) from cross section A, simulated from April 2018 to May 2021. Results are displayed as thermal cycles of rock temperature and **a-d** showing the horizontal displacements and **e-h** vertical displacement, for P1 to P4 respectively. Positive values of horizontal displacement depict movement toward North, whereas negative vertical displacement describe a downward movement.

The vertical displacements had negative values (i.e. moving downwards), and a steep trend with small incremental values after each cycle. For instance, slab 1 (Figure 6-14e) had constant cyclic increases of $\Delta 0.2$ mm for ISO models, whilst the ANI results showed an increment of $\Delta 0.1$ mm after each complete cycle (i.e. after 12 months). On average, during one full cycle (i.e. in a range of RT between 15°C and 35°C), the vertical displacement ranges between 0 and -1.2 mm for ISO and between 0 and -0.8 mm for the ANI model. The slab 2 cyclic variations (Figure 6-14f) were about half of the values for slab1, with a vertical displacement increment of $\Delta 0.1$ mm (ISO) and $\Delta 0.05$ mm (ANI) after each cycle, fluctuating on average from 0 mm to -1.0 mm (ISO) and 0 mm to -0.6 mm (ANI) for one cycle. For slab 3 (Figure 6-14g), the differences between cycles were $\Delta 0.02$ mm (ISO) and $\Delta 0.01$ mm (ANI), reaching a maximum vertical displacement of -0.32 mm and -0.25 mm on each cycle, for ISO and ANI respectively. The smallest displacement cycles were observed for the intact rock behind slab 4 (Figure 6-14h), with ISO and ANI values of $\Delta 0.01$ mm and maximum vertical displacements of -0.18 mm per cycle. Overall, a dependency of the displacements with the RT was evident across all surveyed points and models for the simulated

period. The ANI models had smaller horizontal displacements than the ISO models, whilst both reached displacements smaller than 0.5 mm for P3 and P4, where RTs fluctuated $\Delta 10^{\circ}\text{C}$ at most.

6.8 Analysis and Discussion

6.8.1 Thermo-Mechanical assessment of Modelling setup and input parameters

Thermal boundaries (i.e. low, middle and top regions) interacted dynamically between each other throughout the simulation time by changing their extension and magnitude throughout the year. This interaction is based on the in situ observations captured by the infrared thermographic system, considering the morphology and ambient parameters to develop the thermal boundaries. In addition, the use of periodic sinusoidal thermal functions based on yearly and daily RST fluctuations helped test the transient response of the system and its influence on the RT distributions and displacements across the rock mass. Oversimplification of the thermal boundaries may limit the reliability of the modelling results (Marmoni et al. 2020) and therefore requires testing. In our model, the grid at the regions between the slabs had higher zone density than the other areas of the intact column to prevent generating artificial stress concentrations and strong gradients (Itasca Consulting Group 2019).

The thermo-mechanical response of the slabs and the rock column are impacted by the presence of vertical joints (i.e. J1, J2 and J3), which not only created the rock slabs (i.e. S1, S2 and S3) but also affect the thermal conduction of the rock mass and, therefore, the stress distribution. The thermo-mechanical impact of the joints can be associated with their properties, such as infilling, spacing and orientation, which has also been indicated in the findings from Fiorucci et al. (2018). Our modelling results showed that the thermal properties of open joints, with lower thermal conductivity than the intact rock, tend to result in higher rock temperatures (RT) at the outer slab S1. On the other hand, when joints are modelled as closed and thermally continuous, the RT distribution results in deeper isothermal lines which reaches RT values above 20°C even behind S3. Whereas in the open-joint case, the heat propagation takes place before J3, not largely impacting the rock column behind S3, with the deepest RT changes observed closer to the surface. Hence, thermal discontinuities are a necessary feature when assessing the thermo-mechanical performance of the simulation, obtaining results which may fit better to measured data.

6.8.2 Comparison Between Modelled and Measured Data

Numerical model results of the rock temperature (RT) and the horizontal displacement (i.e. xx-displacement) were retrieved as an hourly time-series at a similar location of the in situ rock surface temperature sensor and crack meter, modelled in FLAC® at cross-section B (Figure 6-4a and Figure 6-12a). The seasonal and daily variations of the RT, associated with the thermal

boundary functions, induced displacements in the lateral fracture that are reported as fracture opening (FO) values for both the elastic isotropic (ISO) and anisotropic (ANI) constitutive models. This resulted in a cyclical response of the lateral fracture between April 2018 and May 2021.

A comparison of the RT data was conducted using the measured data together with the fitted average (avg.) function against the results from the simulation (simulated data, Figure 6-15a). Correlation coefficients (R^2) were calculated for the time-series (Figure 6-15b) resulting in 0.86 when comparing the measured against modelled data, and 0.94 for the average function against modelled data. Annual trends closely match the measured and simulated data, however, there is a delay in the peak values between the average function and the simulated data. For hourly fluctuations, the measured data are not exactly represented in the model, because the input functions are designed to capture daily variations rather than hourly fluctuations, considering the thermal steps achievable within a practical timeframe in the numerical model. This relates to the model limitations, which determines the ratio of thermal conduction to mechanical timesteps (i.e. time needed for the conditions to propagate from one node to the next one) based on the model properties (e.g. geometry, intact rock properties, etc.), resulting in different time intervals of calculations for section A and B, as well as a numerical discontinuous inputs from the thermal boundary functions. If the functions had large fluctuations in short timesteps, the model could generate large strains and the thermo-mechanical solution would be unbalanced. This is why a coarser function was used in this research, (i.e. smaller fluctuations in large timesteps) with daily variations instead of hourly fluctuations.

The FO values were compared as time-series (Figure 6-15c), highlighting the delay between peaks in the average function data and simulated results for the ISO model. Unlike for the RT, peak values for the average function happen 15–20 days prior to the peaks from the model and with an approximately 20% longer time duration than the simulated results. In addition, the trend from year to year is increasing; however, this was not achieved by the numerical model. This may relate to the limitation of modelling in 2D on section B, that included the geometry of S1, whereas both S2 and S3 also assist the fracture opening fluctuation processes and their contributions are neglected in this cross-section. Nevertheless, the R^2 values (Figure 6-15d) show a correlation of 0.9 between the average function and simulated data, whilst the measured-to-simulated data correlation was 0.79.

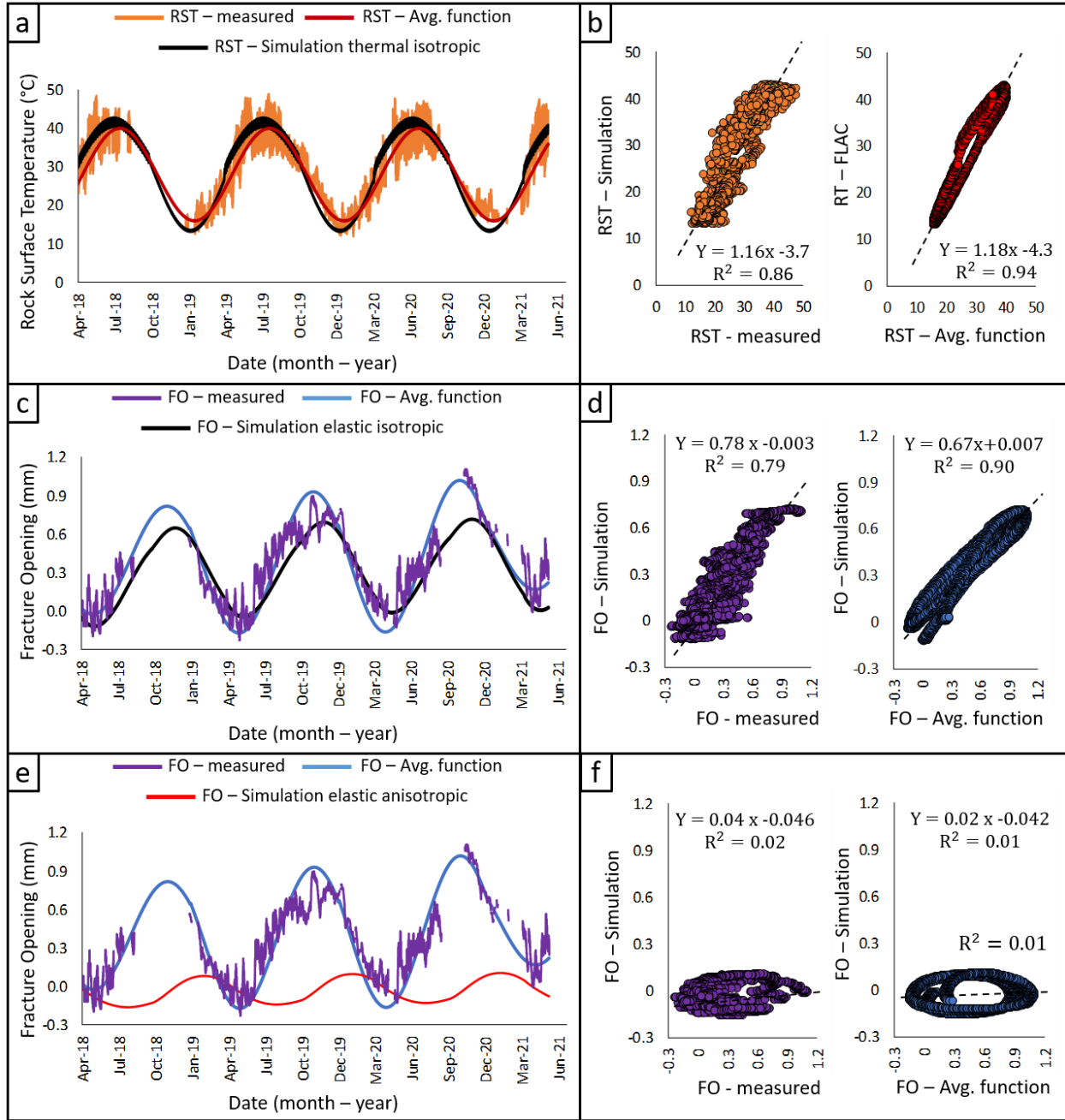


Figure 6-15: Elastic isotropic and anisotropic thermo-mechanical model results for cross section B, at survey point FO (Figure 6-12). Thermal isotropic properties were used, and results for the a) rock surface temperature time-series, are compared in b) scatter plots of data from measurements and average function (Figure 6-8). Fracture opening (FO) values are extracted as the horizontal displacement from the model, as it reflects the orientation of the crack meter in the field. The FO time-series for the observed period (April 2018 to May 2021) and the comparison to measured and average function for both elastic isotropic c), d) and elastic anisotropic e), f) are illustrated respectively.

Comparatively, the ANI models delivered results that neither matched the measured nor average functions of FO data. They showed a shift up to 120 days and reached displacements one order of magnitude smaller than measured, as displayed in Figure 6-15e, f. This low performance from

ANI models can be related to the large contrast of elastic parameters inputted for each plane of isotropy (Table 6-4), despite the micritic limestone being characterized as having a low anisotropy when examining elasticity, yet a moderate anisotropy in strength (Alcaino-Olivares et al. 2022). The numerical inputs were selected to highlight the differences between the ISO and ANI models, considering the computational time and the convergence criterion as well. Therefore, the ANI model with smaller contrast between elastic inputs would tend to perform like an ISO model which inputs are the average of both planes of isotropy for ANI models. This implies that heat fluxes and thermal deformation vectors would be similar to those from ISO models. Numerically, the best fit for simulated data and measured data was obtained from the ISO models.

The cyclic response of the lateral fracture to the repeated thermal loading is a result of the rock mass and environmental conditions of the site. Therefore, the link between FO and RT over the simulated time (i.e. April 2018 to May 2021) was introduced in the thermo-mechanical cyclic plot (Figure 6-16). A yearly comparison for ISO models showed that the simulated data achieved about 60% of the FO of the average function data (Figure 6-16a), with a 20% wider range of RT. The ratio of FO to RT was 0.05 mm/°C and 0.02 mm/°C for the average function and FLAC® data, respectively. Nevertheless, the cycles of daily average values are closer with ratios of 0.04 mm/°C for measured data and 0.03 mm/°C for FLAC® results (Figure 6-16b). The differences between the modelled and measured results could be associated with the simplification of the cross-section B which required (1) the use of GSI for calculating the rock mass stiffness yet not including the structural features explicitly modelled which may underestimate the influence of these joints on the rock mass properties, (2) the thermo-mechanical effects of S2 and S3 on S1 which are not accounted for the cross-section B, and (3) the lateral fracture extension between the rock column and the adjacent cliff which is not uniformly shaped in 3D (i.e. not planar). Therefore, this study shows the importance of suitable site instrumentation, reliable data acquisition and the adjustment of numerical models to actual rock mass behaviour, which have been pointed out by several authors already from other locations where thermo-mechanical proofs were documented (Greif et al. 2006, Bakun-Mazor et al. 2013, Vargas et al. 2013, Guerin et al. 2019, Villarraga et al. 2021, Grechi et al. 2021).

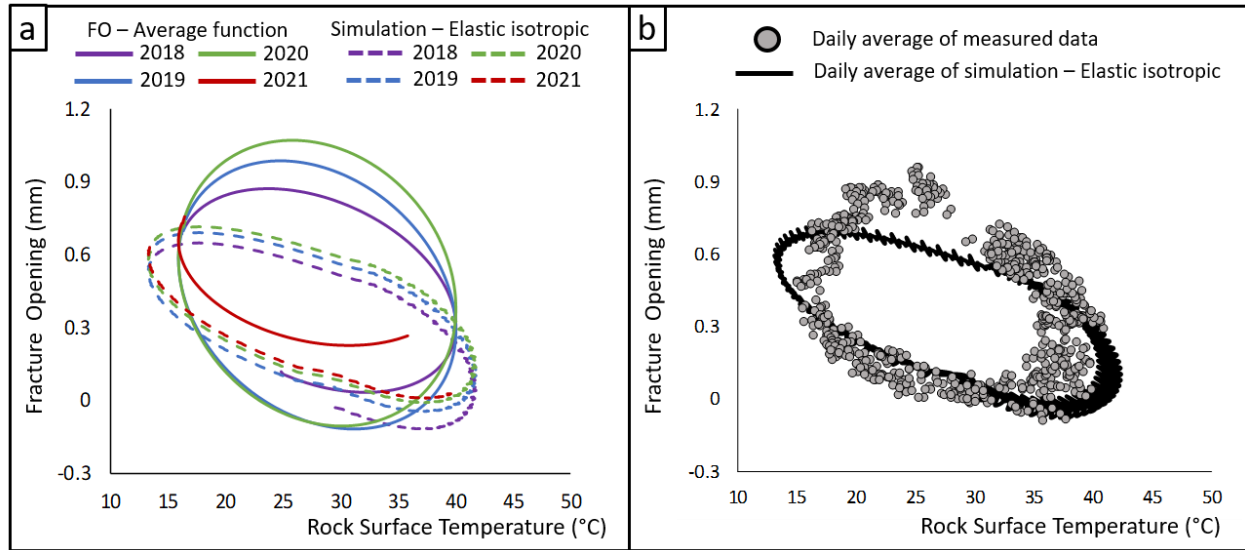


Figure 6-16: Thermo-mechanical cycles of fracture opening (FO) as a result of rock surface temperature (RST) for the elastic isotropic model. Simulation results are plotted as a) the average value per day between 2018 and 2021 (i.e. one curve per year with 1 datum per day within a year) compared to the FO averaged function of the measured data (Figure 6-8) and simulation results for the elastic isotropic conditions (Figure 6-15). In addition, b) a comparison between daily (dots) average value (i.e. average value for a single day using the 2018 to 2021 data set and 365 days) for measured data compared to the results from FLAC® (solid line). The definitions and calculations used are presented in Section 6.6.2.

6.8.3 Observations of Rock Mass Behaviour Under Thermo-Mechanical Cycles

The monitoring station installed in the KV has followed similar practices and the data has shown similar findings to the referenced case studies from Table 6-1. Most importantly, the implementation of the IRT led to the definition of the thermal boundaries, whilst the crack meter measured displacements of maximum around 1.2 mm. In general, the thermo-mechanical effects are seen in a wide range of lithologies, morphologies and ranges of temperatures (Hall and Thorn 2014). However, the recorded displacement magnitudes are usually on the order of 1 mm, with few exceptions, such as when accelerated ground movements are measured (Greif et al. 2006). Small displacements (i.e. < 1 mm) are observed at different sites to be reversible, oscillating around fractions of mm, which increases with time. In both cases, the data usually show short irreversible displacements, associated with fracture propagation, which are typically unnoticeable at the outer face of the rock mass (Vlcko et al. 2009, Bakun-Mazor et al. 2013, Collins and Stock 2016, Alcaino-Olivares et al. 2021). These changes will impose new stability conditions for the rock mass, even at the actual fracture tip which may hold unbalanced stress intensity values until a new opening occurs. The present study is a preliminary modelling exercise to help better define the elements that should be captured in a more complex 3D model to be run in the future. The influence of the thermal boundaries and the geometry of the rock column modelled in 3D could lead to a better representation of the complex deformation and crack development at the

site. Likewise, the 2D cross sections modelled in the present study help understand some aspects of the rock mass behaviour, such as the influence of the cyclic nature of the deformation and if irreversible displacement could be expected.

6.8.3.1 Cyclic deformation

The differences between the simulated data (i.e. purely thermo-mechanical effect) and the measurements can be related to other driving mechanisms, such as changes in humidity or vibrations, which were not accounted for in the presented simulations, as well as crack growth and failure (e.g. Atkinson 1984, Freiman 1984, Potyondy 2007, Nara et al. 2013, Nara et al. 2017). Reversible (i.e. hourly and daily to monthly cycles) and irreversible (i.e. long-term fracture aperture increase / propagation) displacements of the FO throughout the monitored period were recorded by the data acquisition system on site. The simulated data came from an elastic thermo-mechanical model with plastic joints, delivering cycles of reversible displacements and irreversible displacements linked to temperature fluctuations. The reversible cycles shown in Figure 6-16 have an annual rate of 0.8 mm/year (absolute FO value in a year, minus differences between irreversible displacement) and a ratio of 0.03 mm/°C (see Section 6.6.2). The lateral fracture could propagate downwards until the rock column reached failure due to thermo-mechanical fatigue processes, however, more recent indicators on the rock column (i.e. gypsum markers) and historical photographic evidence suggest that the fracture growth may occur in stages inside the rock mass rather than continuously at the exposed surface (Figure 6-2). In recent years, the research focus has been on assessing geometrical and structural features of intact rock and rock masses and the interaction with the thermo-mechanical response (Woodman et al. 2021, Marmoni et al. 2020, Grechi 2022). Despite our expectation that in situ thermo-mechanical processes may lead to irreversible displacements through fatigue mechanisms for the lateral fracture, the simulated irreversible displacements do not relate numerically to plastic behaviour but were found to be the result of heat accumulation in the model.

6.8.3.2 Irreversible deformation

The measured FO displacements followed a yearly trend (i.e. rising with warmer temperatures), which also accounted for irreversible displacements as plotted in Figure 6-16, with an annual rate of 0.2 mm/year (average FO difference between years) and a ratio of 0.01 mm/°C (see Section 6.6.2). The simulated results presented in this work account for elastic deformations of the rock mass, however irreversible displacements of 0.05 mm/year were obtained by the simulations. These modelled values are linked to heat accumulation within the rock mass which conceptually could be dissipated over long periods of time.

Although field data showed FO extending with time (i.e. irreversible displacement), the modelled values do not refer to damage. In reality, the entire rock mass (i.e. rock column and structures) is expected to behave plastically or in a brittle fashion, with increasing displacements and progressive damage related to thermo-mechanical fatigue. Therefore, changes in trends and sharp inflections of measurements happened at different variations of temperatures, aligning with empirical observation from other locations (e.g. Greif et al. 2006, Vlcko et al. 2009, Bakun-Mazor et al. 2013, Collins et al. 2018, Marmoni et al. 2020). For instance, the modelling results for transient joint displacements in the cross section A (i.e. combining normal and shear displacements under plastic conditions for joints, see Section 6.5.3) showed that for the ISO models, J1 had the largest average displacement rate of 1.15 mm/year, followed by 0.80 mm/year and 0.32 mm/year for J2 and J3, respectively. The progressive displacement of J1 (i.e. S1) can be linked to the measured irreversible deformation of the rock column since the crack meter is attached to the western edge of this slab, whilst other joints (i.e. slabs) can contribute in a smaller manner to the general movement even though these are not measured directly at the site. The order of magnitude for joint displacement is similar to the measured rate of 1 mm/year reported by Collins and Stock (2016) from a location in California, USA, in a granodiorite rock mass. Likewise, the order of magnitude of the ISO ratios corresponds to the ones reported from a site in the Baltic Sea (Finland) for a microcline granite rock mass, although the climatic conditions are not alike (Alcaino-Olivares et al. 2021). However, S3 for the ISO model showed a variable ratio of 0.02 mm/°C for 2018–2019, 0.005 mm/°C for 2019–2020 and 0.004 mm/°C for 2020–2021, as well as in the ANI scenario with 0.01 mm/°C for 2018–2019, 0.006 mm/°C for 2019–2020 and 0.003 mm/°C for 2020–2021. Lower rates obtained from S3 are likely associated with the smaller penetration depth of the thermally active layers causing a smaller range of RT ($\Delta 4^{\circ}\text{C}$) and, thus, smaller deformations (Appendix B - 1).

Analytical and numerical models have mainly been explored using 2D simulations for rock masses (e.g. Mufundirwa et al. 2011, Vargas et al. 2013, Vlcko et al. 2014, Marmoni et al. 2020). These might be sufficient from a mechanical perspective, but do not account for the thermal vectors acting from all sides of the rock mass. It is important to understand the capabilities of modelling packages to replicate the transient thermal behaviour and interaction with the rock mass and joints before more complex and intensive modelling is conducted. Such steps form the baseline for more complex models which may deliver not only the study of the progressive thermo-mechanical fatigue processes but also aid in the comprehension of the temporal and spatial interaction between the rock mass and the surrounding environmental conditions. Hence, the different approaches undertaken by the scientific community in recent years have contributed to guiding our research

direction. The next stage in our work aims at analyzing the 3D thermo-mechanical condition of the rock column, isolating thermally driven mechanisms to determine the frequency and magnitude of repeated thermal loads and the transient displacements of the lateral fracture over time. This will lead to a better understanding of the cliff stability under future environmental conditions, which are forecasted to be hotter than experienced locally in the past (IPCC 2014).

6.9 Conclusions

The stability of ancient rock structures is a paramount subject when it compromises the safety of people, such as the case described in this paper for a 15 m tall rock column above the entrance to tomb KV42 in the Valley of the Kings, a valley where tourists visit frequently and archaeological missions work. Our goal was to understand the potential impact of thermal cycles on the rock column behaviour. The present study introduced the structural and rock mass conditions (i.e. fracturing degree), the monitoring system of the site, and the collected environmental information that was used to understand the influence on the opening cycles of a lateral fracture between the rock column and the back cliff.

The measured data helped in identifying the geometrical influence and ambient conditions prone to induce cyclic thermal deformations of the rock column above tomb KV42, particularly the displacement which had a ratio of 0.05 mm/°C. To differentiate between gravitational and thermally induced stresses, a transient finite difference model was built to capture the driving horizontal extension of the fracture opening during the evolution of the lateral fracture with time (i.e. seasonal variation). Crucial model input definitions, such as the extension of thermal boundaries, transient rock temperatures and representative geometries were based on local structural surveys and data obtained from the monitoring system. The simulations were conducted with an isotropic (ISO) and an anisotropic (ANI) mechanical constitutive model, along with representative joint elements for appropriate sections. The results for fracture opening revealed that the ISO models had a correlation value (R^2) of 0.79 when compared to the raw measured data, whilst R^2 is 0.8 when compared to the average function data. However, there was no correlation between measured and modelled data for ANI models found, implying that the micritic limestone at this site tends to behave isotropically when compared to the modelling.

Thermal isotropic conditions were used, with the exception of the vertical joints (i.e. J1, J2 and J3) where different thermal properties were set. The role played by open joints in the heat conduction led to a rise in the rock temperature at the shallow surfaces with an uneven distribution inward so that the thermal interaction with depth was limited by the presence of the joints. Therefore, the simulated displacement rates of the slabs were 1.15 mm/year for S1, 0.8 mm/year for S2 and

0.32 mm/year for S3, which align in magnitude with the reported thermo-mechanical rates of 1 mm/year at other locations (Collins and Stock 2016). The simulated results obtained in this study are promising but do not fully replicate the measured data. To understand the complete 3D movement and potential failure directions a 3D model may better capture the local surface geometry, the lateral fracture extension, as well as the thermal boundaries. Furthermore, the use of a plastic mechanical constitutive model and an elasto-plastic fracture mechanics approach is planned, which will assist in predicting the rate of lateral fracture growth as a result of rock temperature fluctuations. Such predictions are important to better understand the future impact of environmental influences that change with time and will aid in developing preservation strategies for this world heritage site.

CHAPTER 7 TRANSIENT THERMO-MECHANICAL 3D MODELLING OF THE JOINTED ROCK COLUMN USING DYNAMIC THERMAL BOUNDARIES

This chapter expands upon the proof of concept modelling established to capture the thermo-mechanical deformations in the Valley of the Kings, as detailed in Chapter 6 and published by Alcaïno-Olivares et al. (2023). The chapter has used unpublished climatic and deformation values from above tomb KV42 on the jointed rock column, expanding from the previous 2D modelling that ranged from April 2018 to May 2021 and in this section now has included up to July 2023. While the monitoring system permits measurements of only the horizontal displacements of Slab 1, exploring the inputs of relevant features aids in comprehending the stresses acting on the joint surfaces and the thermal boundary conditions. The 3D model is programmed in FLAC3D®7.0, utilizing a complex geometry derived from a Digital Elevation Model (DEM) of the southern side valley surrounding tomb KV42. Building upon the earlier study, this chapter presents measured and modelled results concerning mechanical (principal) and thermo-mechanical (thermally induced) stresses utilizing an elastic Hoek-Brown constitutive model with joint elements to allow for slip and separation of key blocks within the column. The analysis centers on calibrating the model and the prevailing thermal conditions for the first year of records. Further simulations account for sustained inelastic displacements associated with plastic deformations within the rock mass. Additionally, a sensitivity analysis is conducted to assess the impact of input variation on matching temporal fracture opening trends in observed data.

To assist the reader in understanding the large number of simulated scenarios presented in this chapter, a summary of the inputs and model runs for the mechanical, thermal and thermo-mechanical simulations is provided in Table 7-1. Additionally, the optimal set of parameters for calibrating the first cycle, which encompasses 12 months of simulation from April 2018 to March 2019, is also tabulated. The simulation IDs are included to facilitate reference to the relevant sections of this chapter, while the thermal analysis was conducted using properties similar to those in the two-dimensional model. The sequencing of runs is described as follows:

1. Run 00 to Run 18: used to calibrate mechanical parameters.
2. Run 19 to Run 49: Prototyping the thermal model, testing thermal boundary settings and transient conditions. These models are not detailed in this dissertation.
3. Run 50: named as Thermal Model. Simulated temperature distribution using inputs from the two-dimensional model.

4. Run 51 to Run 99: Prototyping the thermo-mechanical model, including the coupling process between mechanical and thermal processes. These runs are not presented in this dissertation.
5. Run 100 to Run 114: Thermo-mechanical models used to calibrate the inputs for the first 12 months of data.
6. Run 115 and Run 116: renamed as Run A and Run B. Differentiated as best-fit models, incorporating the unknown value of the normal-to-shear stiffness ratio for joints.
7. Run 117 to Run 149: Various approaches to calibrate the model over the entire data acquisition period, including plasticity. These trial runs are not presented in this dissertation.
8. Run 149 to Run 156: these runs, introduced in CHAPTER 8, summarize different approaches to modelling fracture growth in the rock column.

Table 7-1: Mechanical and thermal properties used across this chapter. Range of values are given for those properties tested in a sensitivity analysis, also blank space refers to properties that were not included in the analysis. The best fit column is the thermo-mechanical inputs that delivered the best match between measured and simulated data for the first 12 months of simulation. *The shear stiffness value was selected considering the condition of the joint's planes.

Simulation purpose	Mechanical	Thermal	Thermo-Mechanical	Best Fit
Constitutive Model	Elastic, Hoek-Brown, Isotropic	Thermal Isotropic	Elastic Isotropic Thermal Isotropic	Elastic Isotropic Thermal Isotropic
Simulation ID	Run 00 to Run 18	Thermal Model	Run 100 to Run 114	Run A and Run B*
Density (kg/m ³)	2000	2000	2000	2000
Young's modulus (GPa)	10.1 – 17.0		17	17
Poisson's ratio	0.11 – 0.21		0.21	0.21
UCS (MPa)	15 – 55.6		15	15
Tensile strength (MPa)	6.7 – 8.0		8	8
GSI	50 – 70		60	60
Rock – Thermal Conductivity (W/mK)		0.75	0.75	0.75
Rock – Heat Capacity (J/kgK)		750	750	750
Rock – Expansion Coefficient (1/K)		8x10 ⁻⁶	8x10 ⁻⁶ – 10 ⁻⁴	7x10 ⁻⁵
Joint – Normal Stiffness (GPa/m)	82 – 207		210	210
Joint – Shear Stiffness (GPa/m)	20.7 – 207		21 – 210	21* – 210
Joint – Friction (°)	35		35	35
Joint – Dilatation (°)	30 – 35		30	30
Joint – Cohesion (MPa)			0 – 1	1
Joint – Tension (MPa)	0.5		0.5 – 7	7
Joint – Shear-bond-ratio	50		0 – 100	100
Joint – Thermal Conductivity (W/mK)		0.0075	0.0075	0.0075
Joint – Heat Capacity (J/kgK)		750	750	750
Joint – Expansion Coefficient (1/K)		8x10 ⁻⁷	3x10 ⁻⁸ – 5x10 ⁻⁵	7x10 ⁻⁸

Understanding the model's behaviour is essential to further validating the simulation of longer measured data in more cycles. The goal of this chapter is to conduct elastic simulations within a cycle, thus no failure is reached. In subsequent stages, this will be reassessed to incorporate

plasticity for the thermo-mechanical simulations. However, during the mechanical simulations, the Hoek-Brown failure envelope was employed to compare that failed regions within slabs, the notch, and the lateral fracture against site observations. An integrated simulation using both elastic and strength parameters will ultimately determine best inputs.

7.1 Chapter Introduction

The rock column above KV42 exhibits several distinctive features, including subvertical joints that break the column into slabs, a notch section, and the development of a lateral fracture, as illustrated in Figure 7-1a. These features are significant not only for assessing stability (Figure 7-1b) but also due to their thermal impact on the rock column itself. The presence of joints creates a thermal disruption in the otherwise continuous rock mass, allowing air to circulate and limiting temperature conduction, thus confining thermal exchange primarily within the slabs. Conversely, the notch section displays significant temperature variation and serves as a horizontal thermal boundary within the column. This temperature contrast arises from the valley's morphology and the sun's path, which does not reach the notch section for six months of the year. The lateral fracture, extending from the upper portion of Slab 3 to beneath Slab 1 at the notch section, is evident on the outer face of the rock mass, as depicted in Figure 7-1c. Gypsum marks placed in 2017 do not show any continued lateral fracture extension in the outer face of the rock mass (final expression).

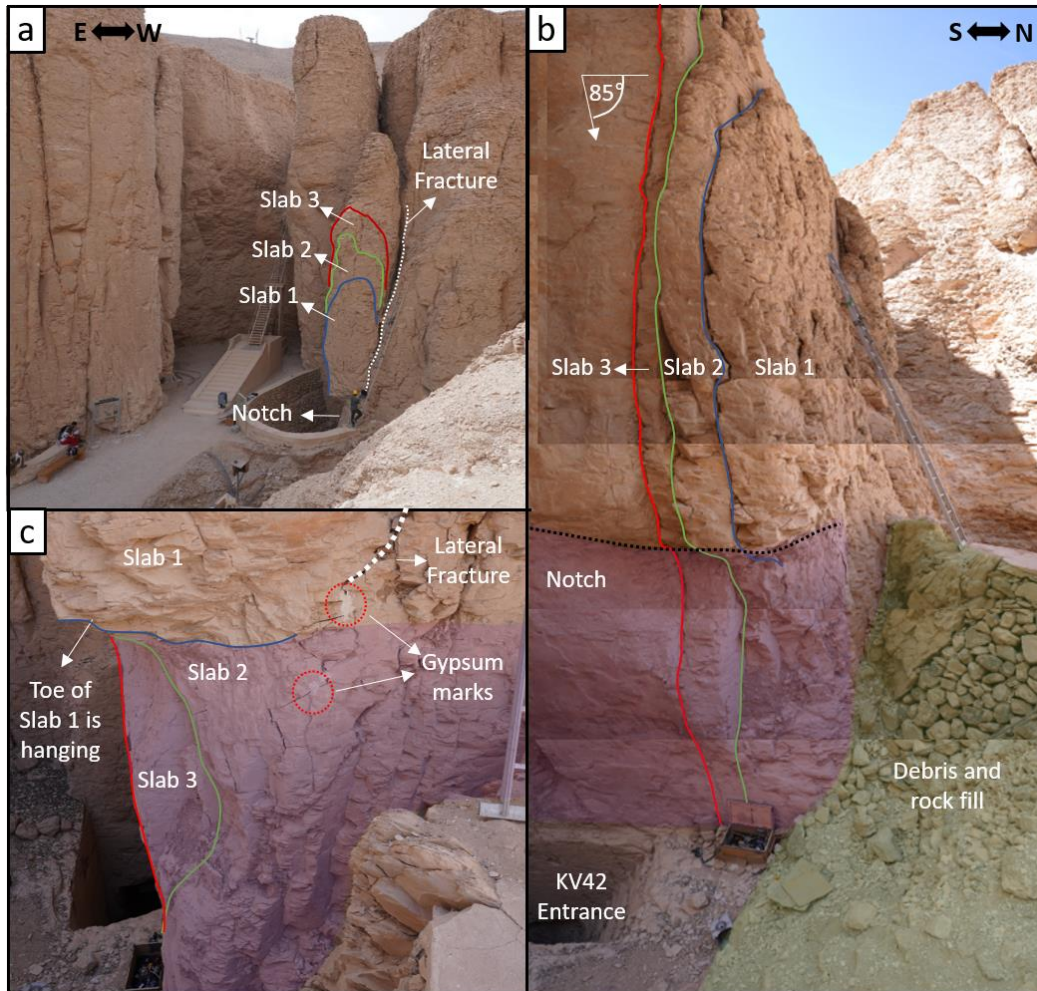


Figure 7-1: Rock mass features in the rock column above KV42, including a) an overview of the site highlighting the main features that influence the stability of the column. The b) south-north section illustrates the interaction between the slabs and their continuity, delineating the boundary with the notch section. The KV42 entrance and the debris level are depicted as part of the column's surroundings. At the notch section, c) a detailed image highlights the slabs and lateral fracture boundaries, particularly where the lateral fracture terminates at the gypsum marks. Pictures taken in March 2022.

As of the publication of this dissertation, the latest campaign at the Valley of the Kings occurred in March 2022, after two years of travel restrictions imposed due to the Covid-19 pandemic, at which maintenance of the monitoring system and geological mapping were scheduled. The monitoring station was still in place, including the infrared thermographic (IRT) station (Figure 7-2a), yet some upgrades were needed to enhance connection and power. The rock temperature sensor and the weather station were cleaned and properly attached to the rock mass (Figure 7-2b), whereas the dendrometer was only inspected to not alter any reading of the lateral fracture opening (Figure 7-2c). The system was connected to the server for remote data retrieval, although missing data was observed afterwards. As depicted in Figure 7-2d, cyclic fluctuations in temperatures and fracture openings were observed, in accordance with the criteria established,

where smaller values indicated closure and larger values indicated opening. It is worth noting that the data from March 2022 do not show any fracture opening value of zero even after a year period, which aligns with previous analysis of sustained inelastic yearly deformation of the Slab 1 (Alcaino-Olivares et al., 2023).

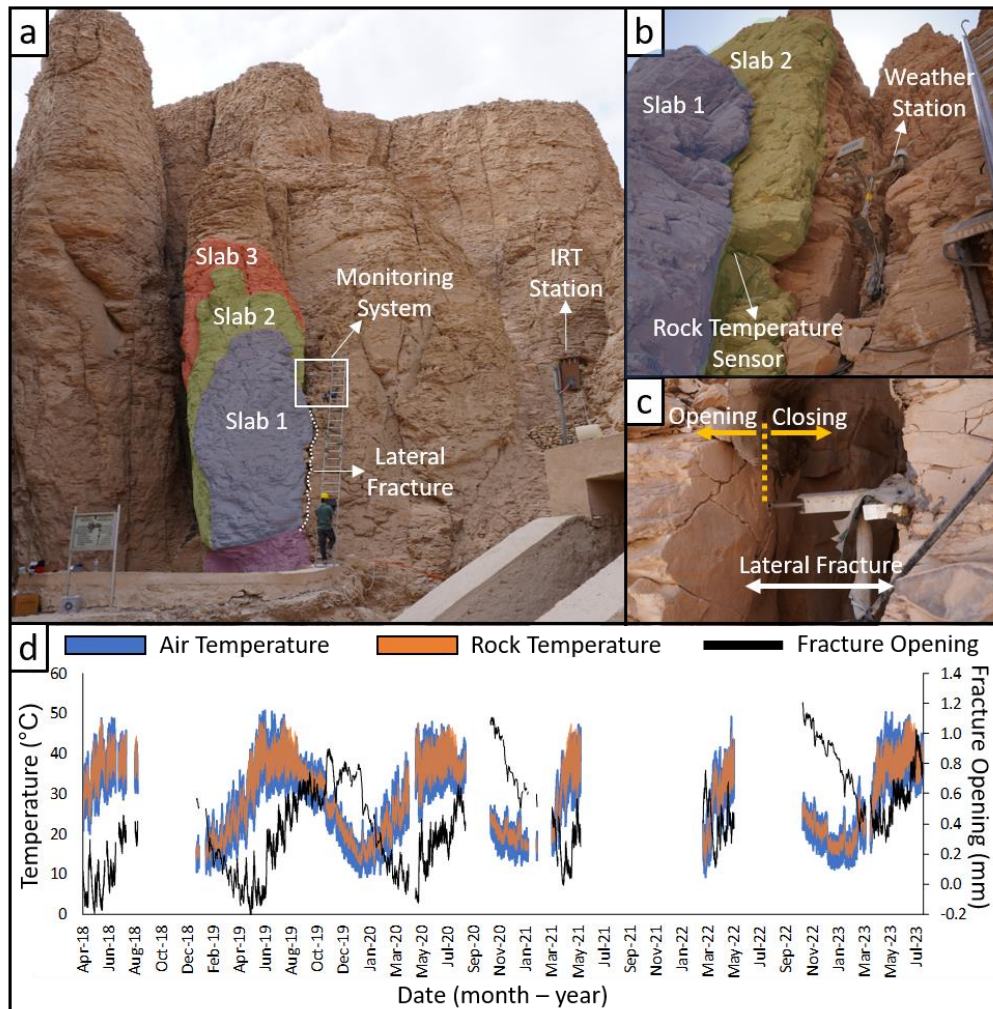


Figure 7-2: Monitoring system in the column above KV42 with available data, showing maintenance in March 2022 of a) the overall monitoring station, which includes the Infrared Thermography (IRT) system and the positioning of slabs and main features. The rock column is instrumented 6 meters above the current ground level (9 meters from bedrock)., where b) the rock temperature sensor and the weather station are installed on the rock surface to locally measure data. The fracture opening is measured just below using a c) dendrometer functioning as a crack meter to record the lateral fracture opening and closure. After carrying out maintenance of the equipment, the d) new acquisition of data for rock temperature and fracture opening until July 2023, which is integrated into a time-series with previous records after equipment maintenance.

The notch section is identified as the primary area contributing to the column's stability, attributed to the strength of the rock mass and the thermal contrast across the column (Alcaino-Olivares et al., 2023). A photographic record dating back to circa 1925-1950, as part of the work conducted by Caroline Ransom Williams (ca. 1925-1950), depicts the state of the notch section at the

entrance of the KV42 tomb, as presented in Figure 7-3a. Through the debris clearance process over the years, the notch section has acquired an even and clear surface, when Figure 7-3a is compared to its condition in March 2022 (Figure 7-3b). It is challenging to theorize the shape of the entire column during the excavation of the tomb. However, considering the overall characteristics of the cliff-tombs, the current column likely formed a tall wall on the western side, completely attached to the entire cliff, naturally covered with debris from the upper mountains. Additionally, it is conceivable that there might have been further slabs associated with the column in the past.

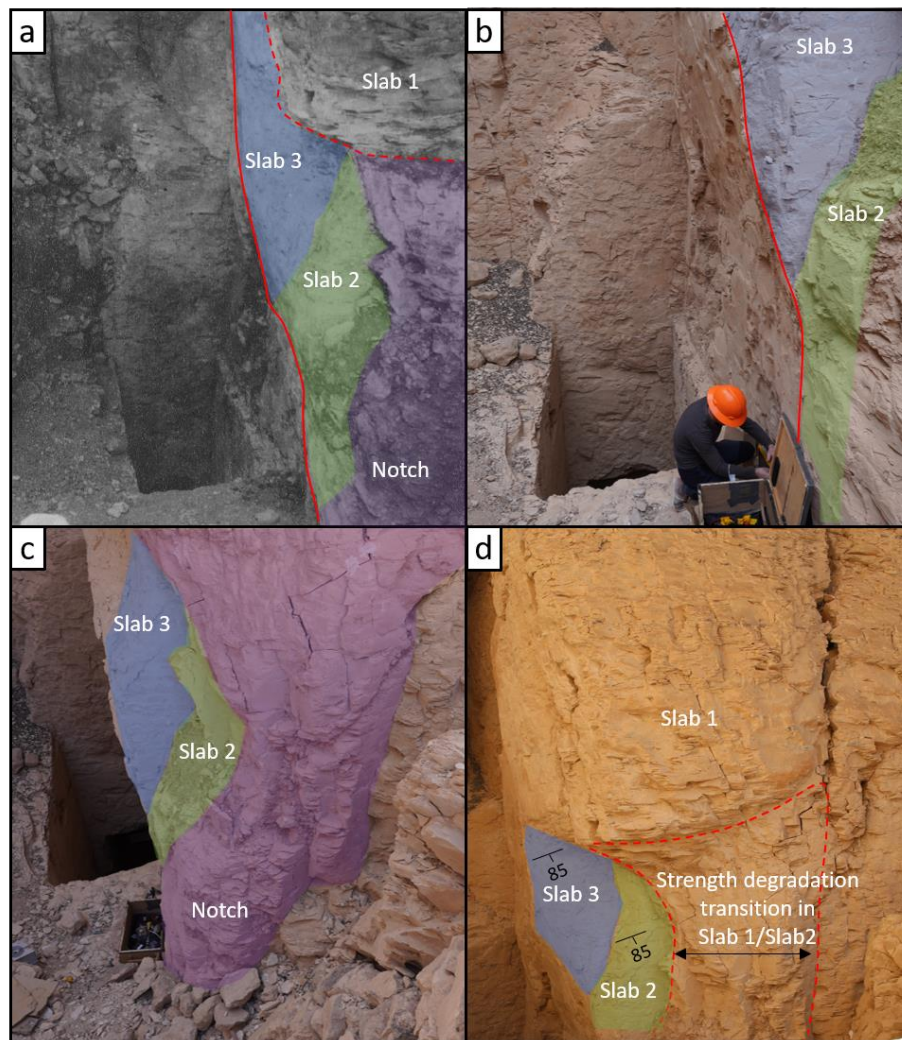


Figure 7-3: The lower part of the rock column above tomb KV42, also known as notch section, is depicted in a) old records captured by Caroline Ransom Williams (MET archives – VK42, ca. 1925-1950), and b) a recent photograph taken in March 2022. In both images, the limits of the slabs are delineated. The c) degraded state of the notch section after several years of human and environmental activities has led to d) a transitional zone for strength degradation which correlates with the loss of the slabs' toe towards the end of the lateral fracture.

Long-term exposure, compounded by factors such as robbery and excavation, debris washing away, or even recent archaeological activities over the last century, could have subjected the notch section to degradation and removal, as depicted in Figure 7-3c. In fact, when observing the notch section perpendicularly, as shown in Figure 7-3d, the visible transition zone of degradation from east to west is evident. This transition cuts out the toe of Slab 1 and progresses towards the lateral fracture end in the West. Consequently, this region is theorized to experience a high concentration of stress, thereby affecting the stability of the column. The process may repeat as the region of Slab 1 at the notch section is removed, advancing to Slab 2 and Slab 3.

In order to quantify the thermal contribution and the measured movement of Slab 1, a three-dimensional model has been developed to incorporate all thermal conditions in a more realistic scenario than the simplified 2D sections detailed in Chapter 6. The understanding of the triggering mechanism can assist in selecting the best option for preservation of the site, and even to forecast fracture extension based on future scenarios with higher temperatures due to climate change.

7.2 Mesh Creation

The process of mesh generation for FLAC3D® encompassed several stages aimed at meticulously delineating zones, endowed with specific properties within the model. The interplay between these zones, at their faces and grid points, contributes comprehensively to the resultant model outcome in terms of stability, accuracy and computational time (Abbasi et al., 2013). Nevertheless, the determination of geometry and zone dimensions depends on the overarching geometric configuration. In cases of simple geometries, where the discrepancy between actual geometry and simple geometrical shapes can be disregarded, the construction of the FLAC3D® mesh may entail computational protraction, yet lacks significant complexity. Complexity emerges when confronted with intricate overall geometries, characterized by pertinent features including the presence of joints, specific regions of interest, and distances between elements smaller than one meter, amongst others. In such scenarios, meticulous control over mesh quality is imperative, necessitating an in-depth examination of zone density and refinement prior to conducting any simulations. To address this exigency, Itasca© has developed a plugin tool to be used in Rhino© which facilitates the mesh generation and manipulation for complex geometries.

The initial geometry was obtained following the work of Lukovic and Ziegler (Lukovic et al. 2021), who were permitted to conduct high-resolution laser scanning of the Valley of the Kings using a Faro Focus 120S scanner. Scanned sections were georeferenced with control points surveyed in the KV area to create a Digital Elevation Model (DEM) with a resolution of 10 cm. For the rock column above KV42, the DEM was trimmed, and contour lines were generated at 1-meter vertical

intervals using ArcGIS. These lines were then imported into Rhino©. Singularities on the ground such as signals, lights, fences, boulders, and piles of debris were removed. Sharp edges and intersection of contour lines on the cliff and column were also edited. Particular attention was paid to the section between the rock column and the rear cliff, where the lateral fracture lies, as the short distance of less than 10 cm (the DEM resolution) caused overlap between the surfaces created. Overall element simplification was tailored to the objectives of the numerical simulation and to reduce the number of zones created to save computational time, resulting in the smoothing of the rear cliff surface and to neglect the top 17 m of the back cliff as a physical component of the model, but rather simulated as a force instead of zones so only 10 m from the current ground level was included. Additionally, the model was centered with the lateral fracture projection on the debris at (0, 0, 0), so that the lateral fracture tip is at 2 m of elevation in the center of the x-axis (West-East) and y-axis (South-North). To ensure further mechanical and thermal stable solutions, the geometry extends 20 m West-East (10 m each side) and 30 m north-south. A comparison between the real case and the wireframe created in Rhino© is introduced in Figure 7-4.

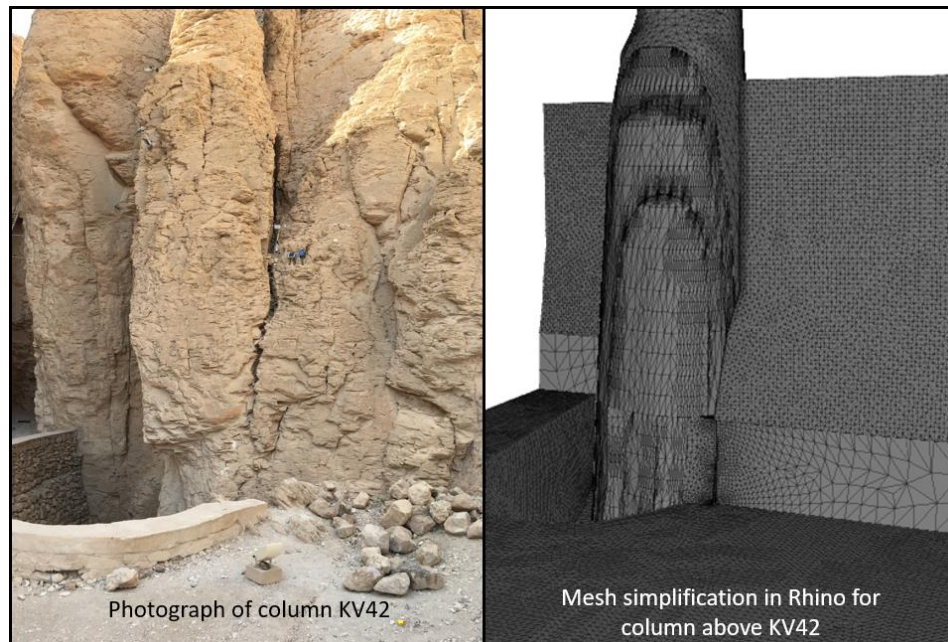


Figure 7-4: Mesh simplification for rock column above KV42, generated in Rhino©, after the work from Ziegler and Lukovic (Lukovic et al. 2021). Simplification are assessed in terms of modelling needs and specific features already detailed in Alcaïno-Olivares et al. (2023).

The poly-surfaces generated from the contour lines were meshed in Rhino©, enabling subsequent differentiation between regions corresponding to the rock column, back cliff, debris layer, and the lateral fracture, as illustrated in Figure 7-5a. Three planes oriented at 000/85 representing the joints Joint 1 (J1), Joint 2 (J2), and Joint 3 (J3), were included, thereby creating three slabs

associated with the joints (Slab 1, Slab 2, and Slab 3). Additionally, the boundary of the notch section was established to commence at a height of 2 m from the current ground level, aligning with the physical lateral fracture location (Figure 7-5b, c).

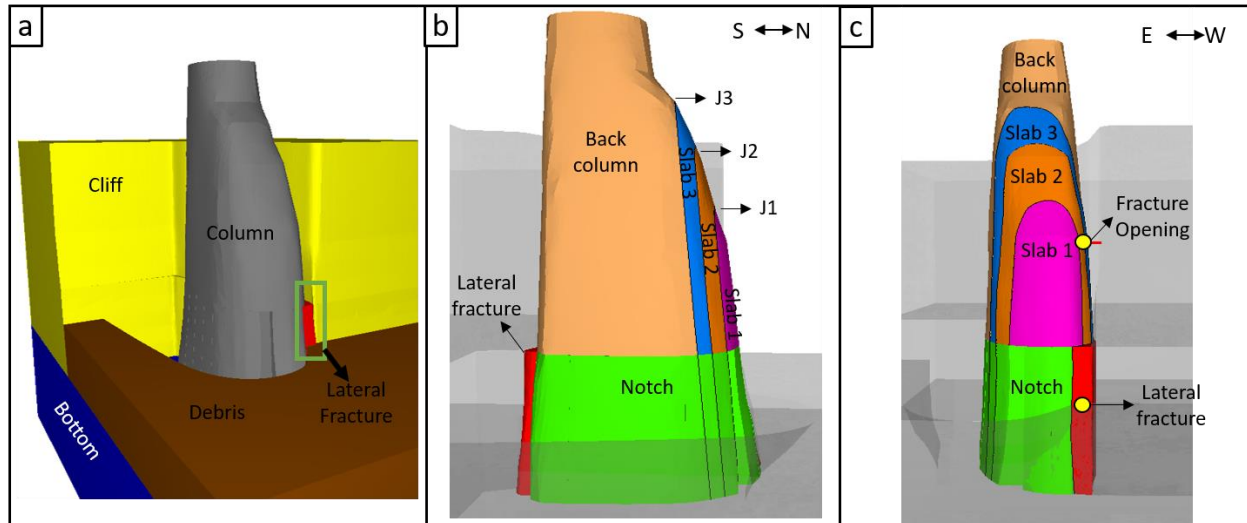


Figure 7-5: Initial meshes for the rock column above KV42, encompassing a) simplification of the general regions of the area. Subdivision were undertaken to generate b) sub-regions within the rock column due to the presence of joints and notches, as illustrated in the profile depicting a South-North section. A c) view perpendicular to east-west delineates slabs and the notch location. The lateral fracture and fracture opening measurement points are highlighted for later comparison between measured and simulated deformations.

To determine the optimal mesh size, consideration was given to features within the rock mass such as the lateral fracture or the width of slabs, which are on the scale of centimeters. This prompted a focus on sizes capable of encompassing the entire region and optimizing the number and length of zones across the small thicknesses. However, it was also essential to capture small-scale values around specific features, such as the notch area, for comparison with measured displacements. Field measurements indicate displacements typically in the millimetre range, imposing the requirement for simulation results to accurately reflect these displacements that are measured at a single point on the Slab 1.

As a result, creating small zones (fractions of meter) could enable the modelling of the measured displacements at a scale similar to the capabilities of the monitoring system and the geological features. Nonetheless, a balance between the number of zones and computational time was needed, as well as to ensure the mesh geometry did not lead to any compromising calculation due to bad mesh elements. Conversely, larger zones might overlook small-scale features by the creation of coarser zones in these areas. In order to test the impact of the mesh zone size, the Griddle tool was used to test different alternatives. Nine meshes were created by changing the

length limits and the gradation factor, which resulted in a range of meshes from coarse (small number of zones) to fine (large number of zones) capturing the specific features.

The meshes were individually input in FLAC3D® for simulating an elastic case with no joints and all models had the same properties (density = 2000 kg/m³, bulk deformation modulus = 3.2 GPa, shear modulus = 2.8 GPa), and their results are plotted in Figure 7-6. It is important to note that results for fracture opening or lateral fracture were surveyed at the locations shown in Figure 6-5c. The criterion for assessing the mesh is to obtain a consistent measure of key outputs even when the number of elements has increased.

The mechanical ratio for each case is depicted in Figure 7-6, ensuring that unbalanced forces in the model will be a fraction of the local forces, thus providing stability in the reported solutions. Consequently, the fewer the number of zones, the lower the mechanical ratio, as unbalanced forces become easier to stabilize. As observed in the plot, the mechanical ratio for models with less than 100,000 elements fluctuate around 0.01 (Std.Dev = 0.006), but varies more for models with 100,000 to 1,000,000 elements. However, it returns to 0.01 when the number of elements is greater than 1,000,000 elements, with a smaller standard deviation of 0.002. Local unbalanced forces for the lateral fracture (Figure 7-6b) and the fracture opening (Figure 7-6c) were also stable when the number of elements was greater than 1,000,000. Particularly, the differences between Case 6 and Case 7 shows a marked change at this point, detailed in Figure 7-6. Since the calibration of the model involved comparing real measurements for the horizontal displacement of Slab 1, the survey of fracture opening (Figure 7-6d) shows the largest displacements when there are more than 1,000,000 elements, which is expected due to the mesh refinement. Additionally, vertical stress values at the lateral fracture point (Figure 7-6e) indicate that when the model has more than 1,000,000 elements it performed better by delivering values close to the calculated vertical stress for 2 m of rock column, resulting in 0.04MPa. Overall, meshes with less elements delivered higher larger variations as standard deviation were found, most likely associated with poor refinements within this region.

Finally, Case 9 was selected, which has a length range between 5 cm to 20 cm for a quad-dominant parameter. The surface mesh was set with a ridge angle of 20°, maximum gradation of 0.05, optimization value of 5 and a shape quality of 0.7. The volume mesh had a maximum gradation of 0.1, a null target size, optimization value of 5 and a shape quality of 0.75. These settings resulted in a geometry with 3,492,557 zones, with 5.25% of them (183,494 zones) within the notch, column and lateral fracture altogether. Table 7-2 shows the zone number per region.

Other alternatives did not converge nor represent clearly the small features when inputted into FLAC3D®.

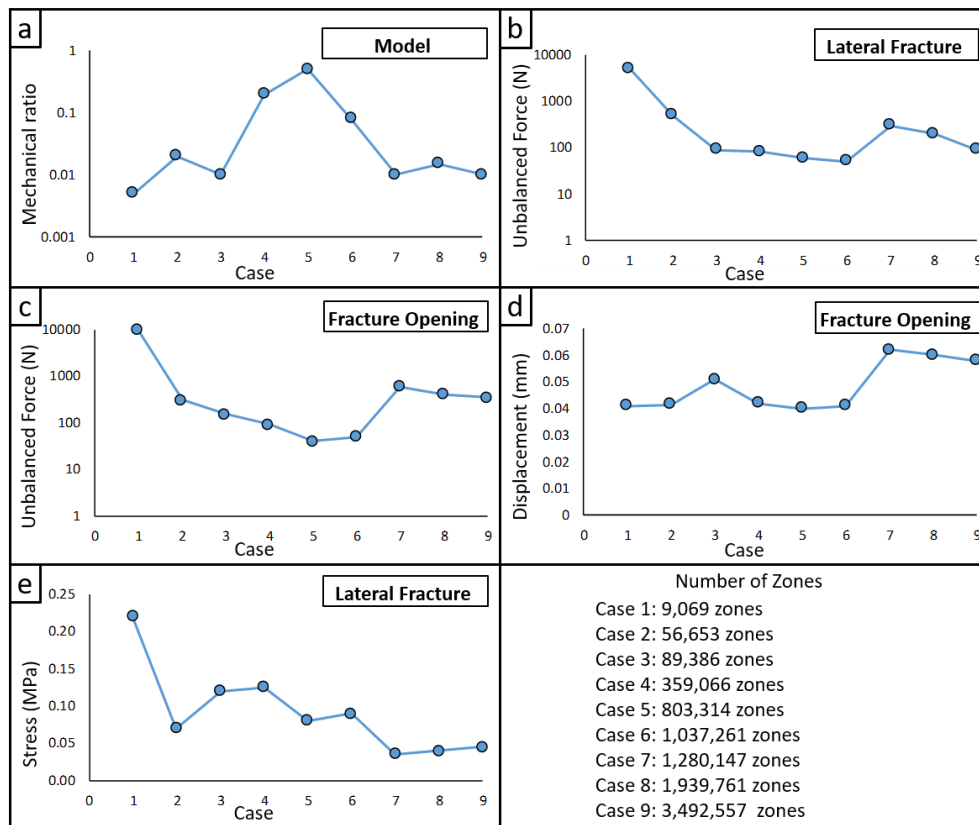


Figure 7-6: Compilation of significant results to compare between nine mesh alternatives modelled in FLAC3D. Each model was characterized by the a) mechanical ratio surveyed across the entire geometry, in addition to the unbalanced forces at the b) lateral fracture and c) fracture opening. Results were reported also for d) horizontal displacements at the *in situ* measured fracture opening location, and the e) surveyed vertical stress at the tip of the lateral fracture.

Table 7-2: Number of zones for the FLAC3D® geometry, created with Griddle, for Case 9 – the mesh geometry used for this study. Note that the back cliff is the region behind the studied rock column which are connected through the lateral fracture. All regions are attached to the bottom of the model.

Region	Sub-region	Number of Zones	Relative number
Rock Column	Slab 1	2,843	0.08%
	Slab 2	4,962	0.14%
	Slab 3	6,777	0.19%
	Notch	31,150	0.89%
	Column	113,608	3.25%
Lateral Fracture		24,154	0.69%
Debris		220,339	6.31%
Bottom		1,454,809	41.65%
Back Cliff		1,633,915	46.78%
Total		3,492,557	100%

The final FLAC3D® mesh (Case 9) is illustrated in Figure 7-7, presenting various perspectives to emphasize mesh continuity and shape. The north-south cross-section (Figure 7-7a) provides an

overview of the model's dimensions, including the extension of the debris layer. Figure 7-7b offers a plan view of the area, revealing the positioning of the column and the simplified cliff face. Additionally, Figure 7-7c presents a perpendicular view, illustrating the elevation of the cliff and the placement of slabs (S1, S2, and S3), with the back cliff's elevation set at 10 m following the removal of its top portion to save computational time.

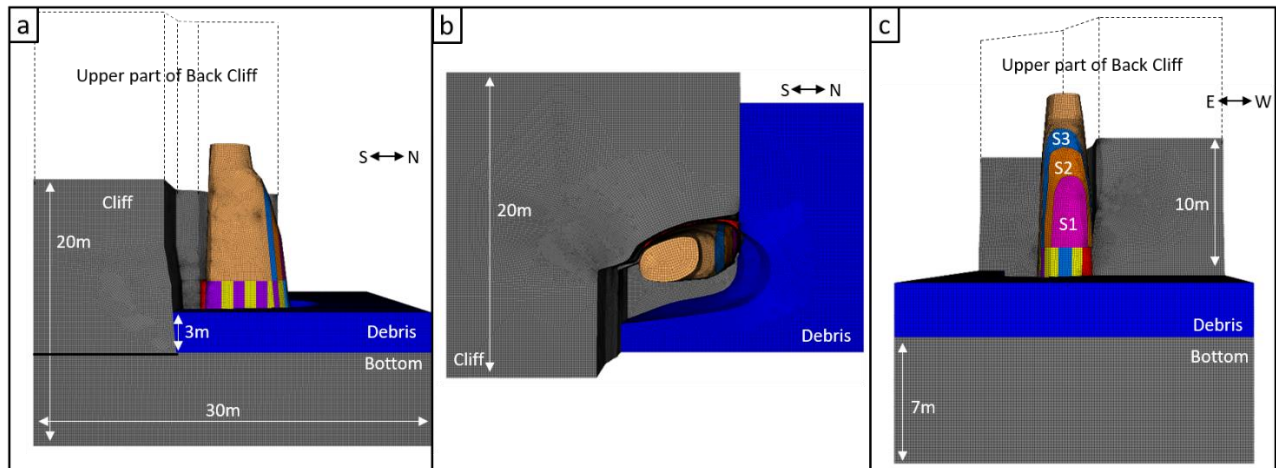


Figure 7-7: Composition of FLAC3D® mesh from different views, after using Griddle volumetric meshing tool. The a) South-North view shows the limit between debris and rock. A b) plan view of the area and c) East-West view of the modelled column shows the simplifications carried out to meshing process.

The careful process of generating meshes in FLAC3D® is vital for accurately representing the intricate shapes and features found at the site, including joints, specific areas, and small-scale differences. Adjusting the density and refinement of zones is crucial to ensure the model remains stable, accurate, and computationally efficient. Utilizing Griddle enabled precise manipulation of meshes, even for complex geometries. By systematically refining meshes and conducting sensitivity analyses, an optimal mesh setup was attained. The chosen mesh, Case 9 with 3,492,557 zones is described in APPENDIX C for zone length and quality.

7.3 Mechanical Numerical Model

The mechanical modelling was divided in three stages aiming to validate the model conditions, such as the boundaries and joint incorporation; as well as to optimize the input selection. An initial set of 16 runs were used to calibrate the rock mass properties, whereas four simulations extra were analyzed for the joint properties. Results are visually compared between simulations displayed as coloured sections of displacements, stresses and the state of zones whenever plasticity was set.

7.3.1 Mechanical settings

The mechanical simulations were carried out using firstly an elastic material behaviour followed by a plastic Hoek-Brown constitutive model. Only the plastic analysis included the presence of joints, which were added as interfaces in the model. The interfaces were defined to mark the edges of the slabs found in situ and represent these key joint surfaces. Figure 7-8 introduces the location and definition of joints as interfaces in FLAC3D®, for Joint 1 (J1), Joint 2 (J2) and Joint 3 (J3). The lateral fracture was modelled as a joint in some instances, in the further long-term mechanical simulations.

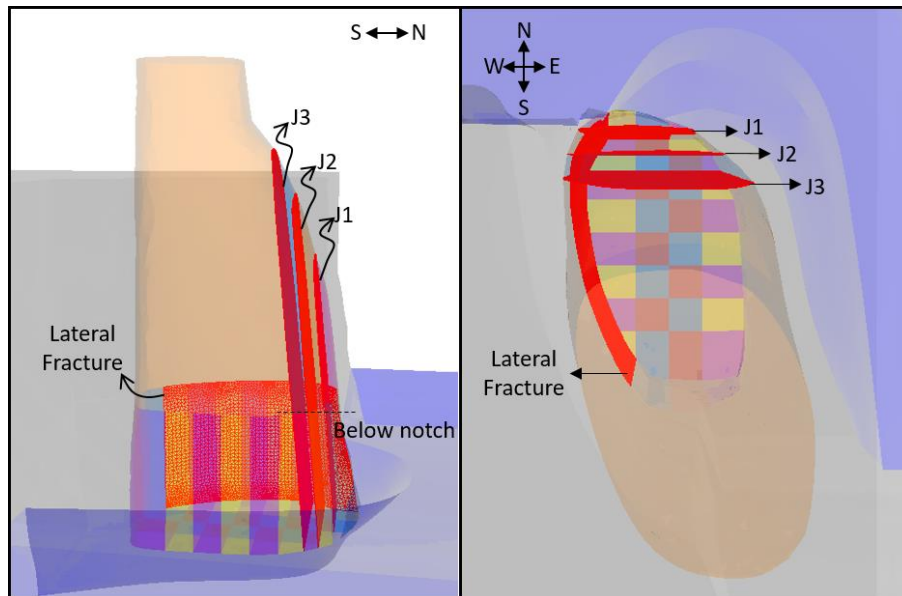


Figure 7-8: Definition of discontinuities in FLAC3D®, marking the presence of joints. Lateral fracture is not defined as a joint, however its location it is highlighted in the figure only. Discontinuities are coded in FLAC3D® as interface elements.

The rock mass properties were inputted following the bi-dimensional model's results (Alcaino-Olivares et al. 2023) for the elastic case to initialize the stress field. Afterwards, the plastic scenario (Hoek-Brown constitutive model) was modelled with a sensitivity analysis over the intact rock properties as detailed in Table 7-3.

The Hoek and Brown intact rock value m_i ranges from 2 to 8 for the micritic limestone, as calculated from the ratio between uniaxial compressive strength (UCS) and tensile strength, detailed in Table 7-3. This range reflects the strength properties of the rock within the measured values outlined in Table 5-4, and is consistent with the m_i values reported by Hoek (2007) for fine and very fine grained sedimentary rocks, including claystone, shales, marls and micritic limestones. As characterized in CHAPTER 5, these lithologies are predominant in many members of the Thebes Limestone Formation, which hosts the studied rock column.

The D constant was fixed at 0.5 for all scenarios, as this value was found to better represent the disturbance of the rock mass. On one side of the rock column, the area was excavated in ancient times with hammer and chisel to construct the portal of tomb KV42, which involved improvements at the eastern wall of the column and the notch section. The western edge has been subjected to natural expansion of the lateral fracture which hypothetically relates to the condition of the eastern side; however, the western side is observed to remain undisturbed. Given that the rock column is only 3.5 m wide in the East-West direction, the average of both conditions characterises the rock column for the entire area. According to Hoek and Brown (2019), a value of $D = 0$ represents an undisturbed rock mass which is the rock column state at the western side, whereas $D = 1$ represents a high degree of disturbance, as the works in ancient times. Therefore, an average of $D = 0.5$ aims to account for the degradation of rock strength caused by the historical excavation of tomb KV42, balanced against the undisturbed conditions observed on the western side. The consistent application of this D value across all scenarios allows for a simplified analysis while still acknowledging the effects of disturbance.

Table 7-3: Intact rock properties for sensitivity analysis of the Hoek-Brown (HB) constitutive model. The range of input values covers the intact rock and field measurements, as reported by Alcaïno-Olivares et al. (2022).

Run	Constitutive Model	Density (kg/m ³)	E (GPa)	ν	UCS (MPa)	σ_t (MPa)	m_i	GSI
Run00	Elastic	2000	13.6	0.15	--	--	2	70
Run01	Plastic-HB	2000	13.6	0.16	35.3	7.4	5	70
Run02	Plastic-HB	2000	17.0	0.21	15.0	8.0	2	70
Run03	Plastic-HB	2000	10.1	0.11	55.6	6.7	8	70
Run04	Plastic-HB	2000	13.6	0.16	35.3	7.4	5	50
Run05	Plastic-HB	2000	17.0	0.21	15.0	8.0	2	50
Run06	Plastic-HB	2000	10.1	0.11	55.6	6.7	8	50
Run07	Plastic-HB	2000	13.6	0.16	35.3	7.4	5	60
Run08	Plastic-HB	2000	17.0	0.21	15.0	8.0	2	60
Run09	Plastic-HB	2000	10.1	0.11	55.6	6.7	8	60
Run10	Plastic-HB	2000	13.6	0.16	55.6	6.7	8	60
Run11	Plastic-HB	2000	13.6	0.16	15.0	6.7	2	70
Run12	Plastic-HB	2000	13.6	0.16	15.0	6.7	2	60
Run13	Plastic-HB	2000	13.6	0.16	15.0	6.7	2	50
Run14	Plastic-HB	2000	13.6	0.16	55.6	8.0	8	70
Run15	Plastic-HB	2000	13.6	0.16	55.6	8.0	8	60
Run16	Plastic-HB	2000	13.6	0.16	55.6	8.0	8	50

The debris layer, as top soil, was modelled with Mohr-Coulomb, with a friction angle of 30°, dilation of 10° and a cohesion of 0.2 MPa. The rock mass strength for all scenarios is shown in Figure 7-9 in the σ_1 - σ_3 space, representing all rock mass strength scenarios associated with intact rock properties and assessment of the rock mass condition that are reflected through the plotting of different failure envelopes. Properties for interfaces were taken from Alcaïno-Olivares et al. (2023),

as bonded interfaces with a shear-bond ratio of 50% for the joints, so sliding will occur when this ratio is surpassed. Interface properties for all joints were: Normal Stiffness (K_n) = 207 GPa; Shear Stiffness (K_s) = 207 (GPa); Friction angle = 35; Dilation angle = 30; Tension = 0.5 MPa; shear-bond ratio = 50.

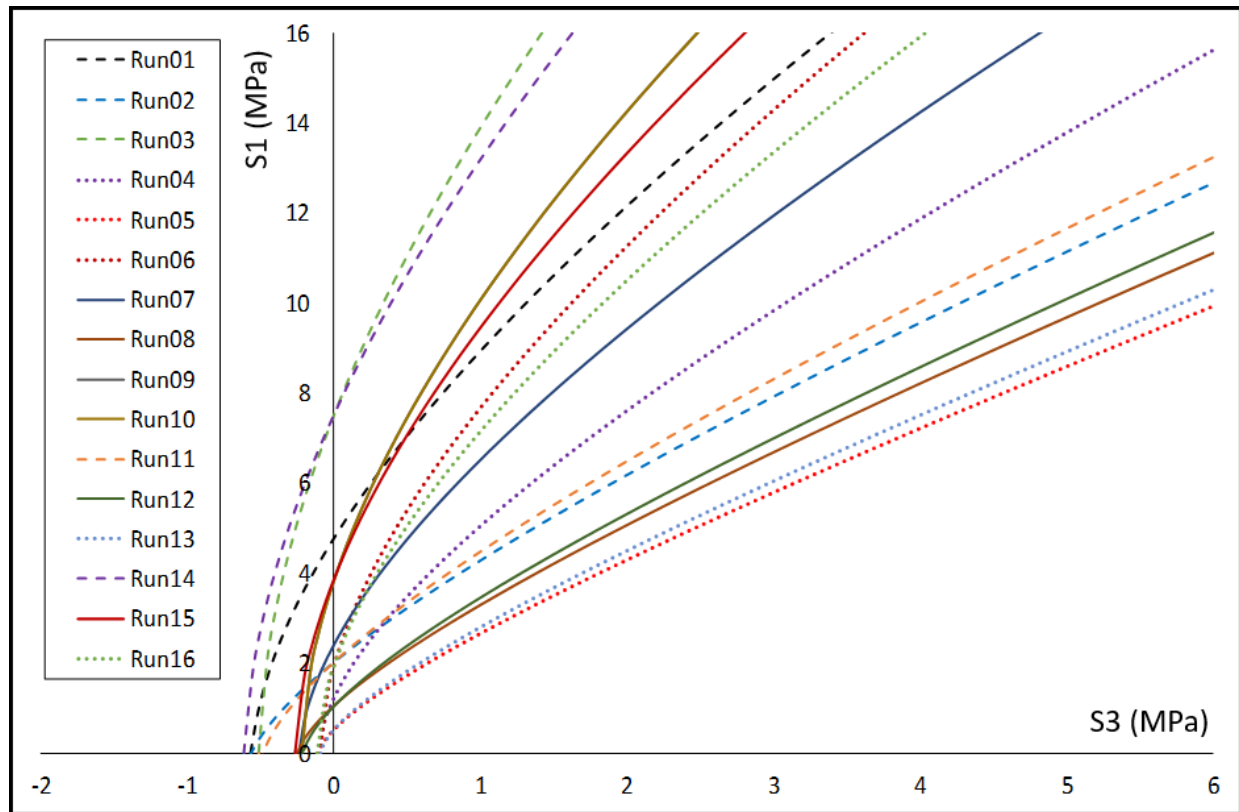


Figure 7-9: Strength limits for different scenarios from Table 6-2. S refers stress and the number corresponds to the minor and major principal stresses.

The coordinate system origin was set at the intersection between the lateral fracture and the debris layer. Hence, the boundaries at East and West (x-axis) are 10 m and -10 m, whereas the South and North (Y-axis) boundaries are at -20 m and 10 m, respectively. These boundaries were restricted for lateral movements. The horizontal boundary at the bottom of the model is at -10 m, which was restricted for lateral and vertical movement. The upper boundary followed the simplified topography, with no restrictions for movement either laterally or vertically. An initial stress condition of 0.034 MPa (oriented downwards) was set to represent the rock overburden above the simplified cliff. The models were solved to a ratio of 10^{-6} in all scenarios, including elastic and plastic.

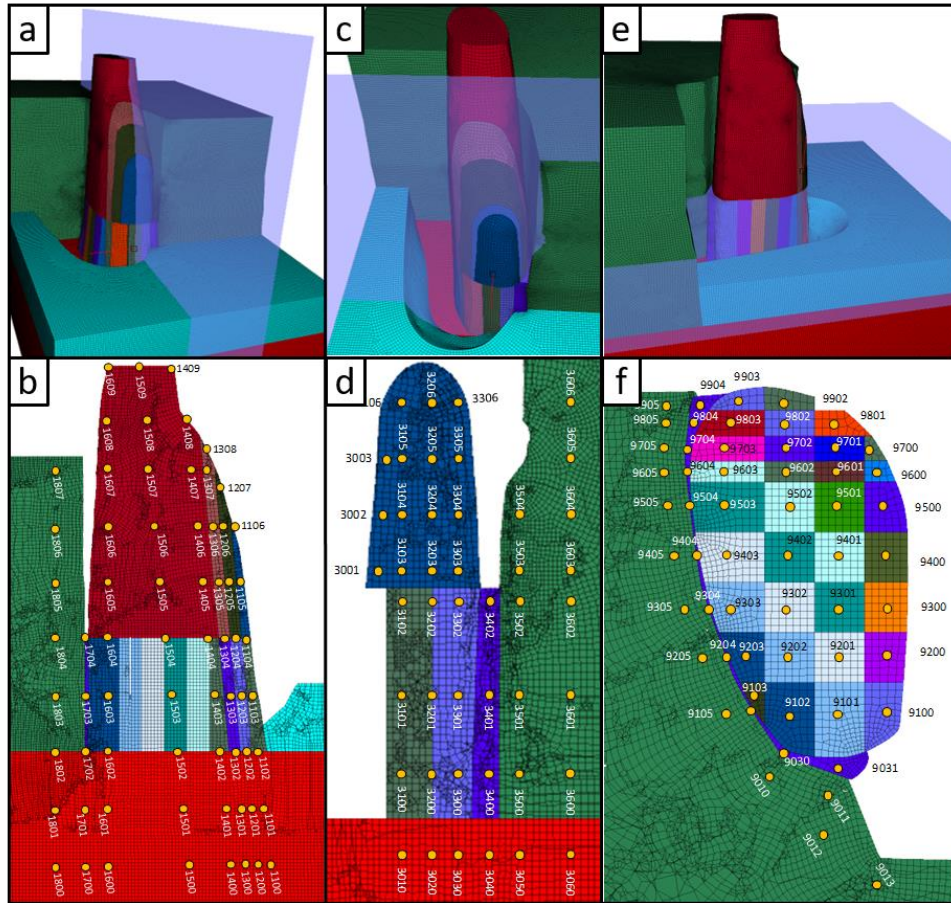


Figure 7-10: : Examples of sampling point location across the simulated geometry to create histories in FLAC3D®. A a) cross section for South-North profile capturing the b) history distribution at the center of the column, including the notch and slabs. Histories created on c) East-West cross section through Slab 1 have d) a regular pattern of sampling points on Slab 1. The e) plan view location at 2m elevation includes f) sampling points in the notch section, lateral fracture and cliff at the boundary between notch and slabs.

Nearly 10,000 histories were recorded, spanning nine sections across South-North (2), East-West (5), and plan views (2). Histories were recorded in FLAC3D® to sample and store data throughout a model run, capturing information at each step or specific intervals. In this model, histories are designed to monitor displacements in all axes, maximum and minimum principal stresses and strains, and the stress and strain tensor. Also, for the monitoring of the stability of the model, the velocity, unbalanced force and condition of zones are also recorded. Figure 7-10 depicts three examples of history location. For example, Figure 7-10a displays the intersection of a cross section with the model, featuring 67 histories distributed across slabs, notch and back cliff as depicted in Figure 7-10b. In the east-west sections (Figure 7-10c), cuts through Slab 1 yield 43 histories spanning the slab, notch, lateral fracture and back cliff, as illustrated in Figure 7-10d. Plan views, such as Figure 7-10e, provide values around the notch section and the lateral fracture (Figure

7-10f). Additional sections available in APPENDIX E. The strategic distribution of sampling points facilitated the parametrization of variables during the analysis of the model results.

7.3.2 Mechanical results

Mechanical analyses were conducted to investigate both elastic and plastic scenarios, employing cross sections representative of the model's behaviour along its three principal axes. The north-south section (Figure 7-11a) offers insight into the mechanical interplay amongst the three joints, providing a detailed examination of their relationships. Conversely, the east-west section (Figure 7-11b) provides a broader perspective, illustrating the comprehensive interaction between the rock column and the lateral fracture. Furthermore, the plan view of the notch section and lateral fracture's top surface (Figure 7-11c) offers a nuanced understanding of the intricate relationship between both features, revealing their spatial dynamics. Notably, control points (Figure 7-11c) serve as focal points for data retrieval, enabling the assessment of displacement at the fracture opening location and the evaluation of the generated stresses at the lateral fracture.

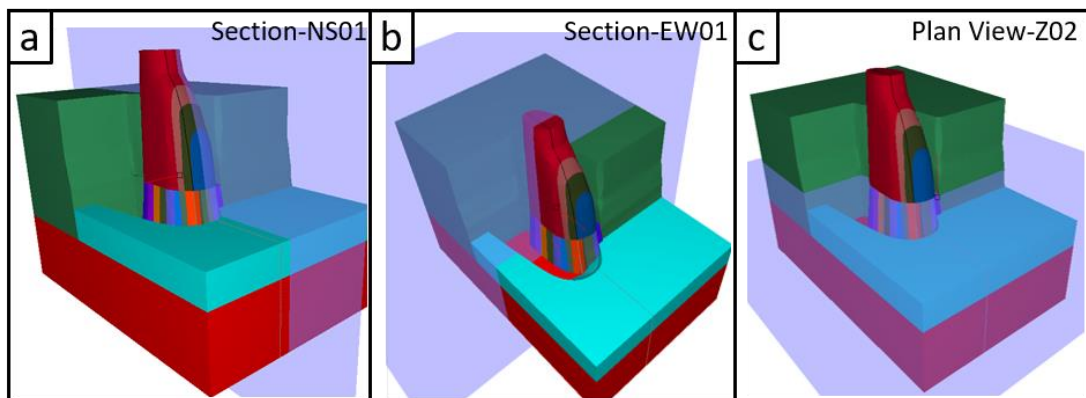


Figure 7-11: Cross section definition for visual report of results, with a) North-South orientation for joint interaction, b) East-West oriented section and c) a plan view at Z=2.

7.3.2.1 Displacements

The magnitude of displacement is reported in Figure 7-12, wherein positive displacements are delineated as directed northwards. While discernible variations between scenarios are not prominently evident, notable displacement magnitudes are particularly observable in the upper segment of the rock column. The displacement vectors exhibit a prevailing orientation towards the south (back) and downward directions, dissipating towards the model periphery, where iso-contour lines converge to constant values. The influence of interfaces on displacement is observed with limited prominence, primarily affecting the mobilization of displacement isolines across joints.

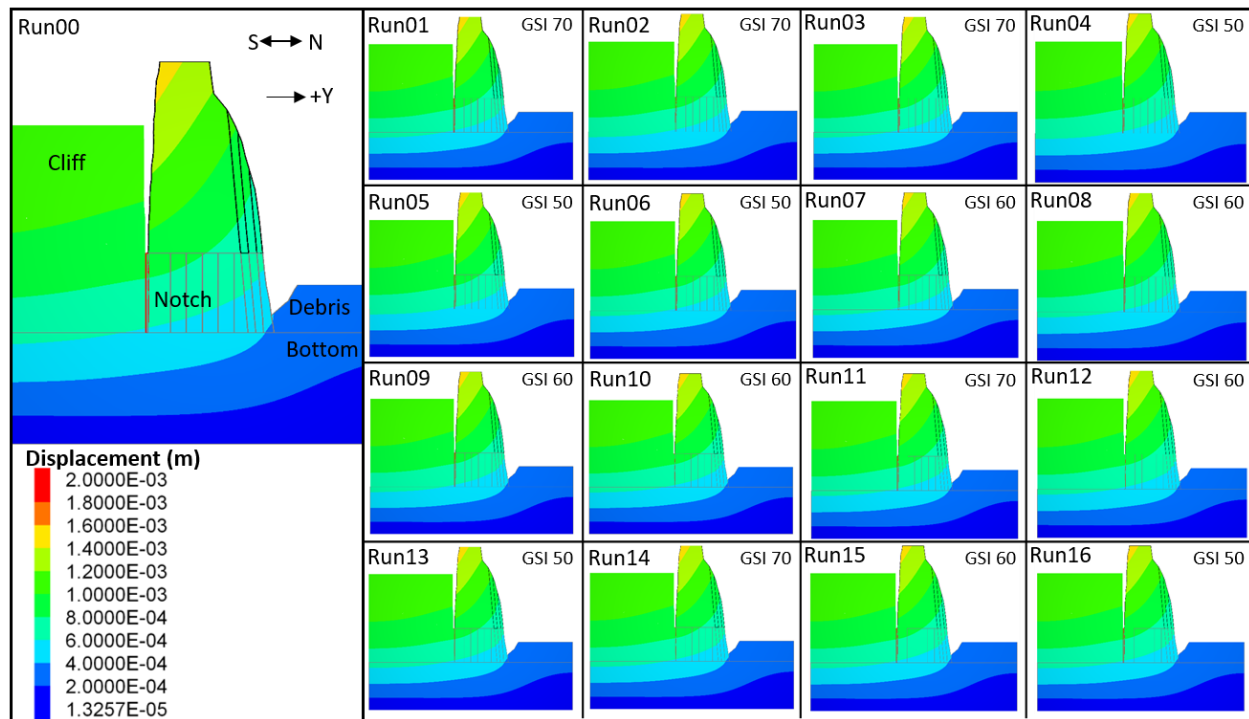


Figure 7-12: Isolines representing the total magnitude of displacement vectors along three axes for each scenario. Model parameters are listed in Table 7-3.

However, upon specifically plotting horizontal displacement in the East-West direction, as depicted in Figure 7-13, discernible disparities emerged amongst various model runs. Particularly noteworthy is the observation of negative motion (westwards) in the region of the rock column proximate to the lateral fracture, spanning from 4 m of elevation at the upper boundary of the lateral fracture. This phenomenon stands in contrast to the overarching inclination of the column eastwards. Reported horizontal displacement ranges extend up to 0.035 mm, with values of 0.06 mm observed at the eastern end of the column at the same elevation, indicating a positive magnitude and an inclination eastward. Instances with lower GSI values exhibited more significant displacements, as exemplified by the comparison between Run 03 and Run 06, wherein the GSI value decreased from 70 to 50, respectively (see Table 7-3). Along the cliff wall, a consistent displacement of 0.02 mm eastwards is reported at the same elevation as the western motion of the rock column. Conversely, regions such as the debris or the bottom exhibit constant displacement values, irrespective of variations in rock properties. Displacements at the model boundary were null indicating stable far-field conditions.

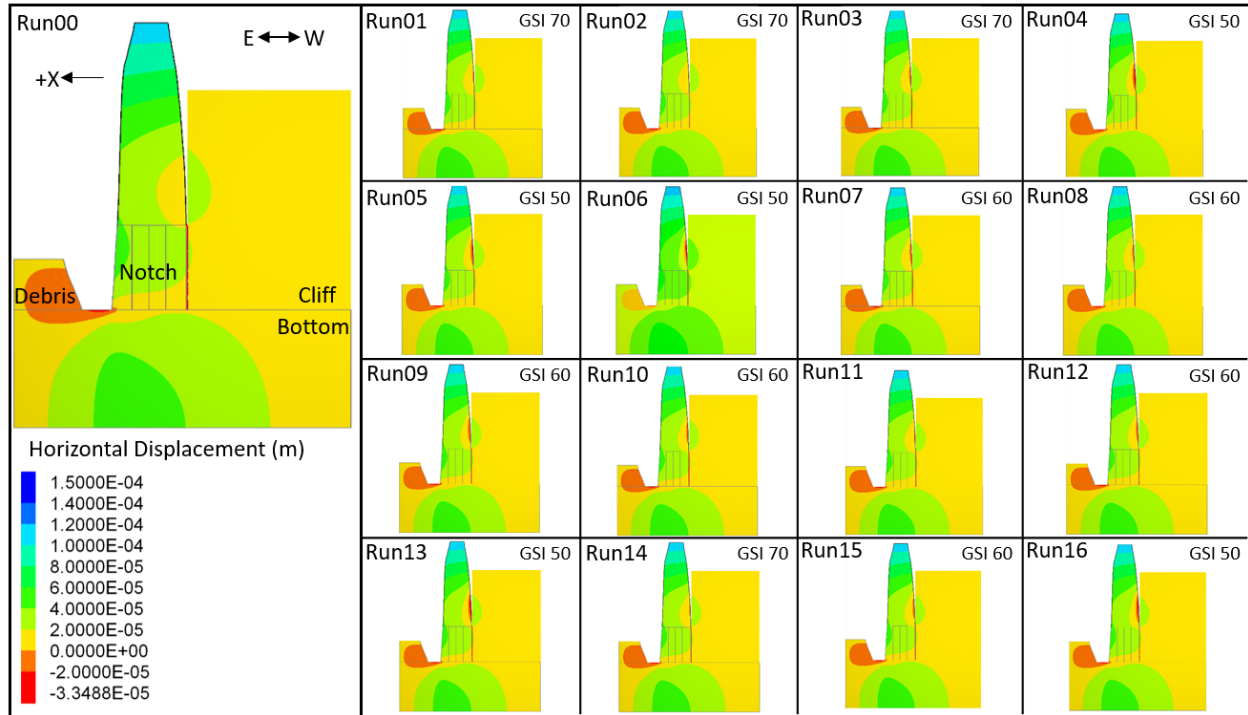


Figure 7-13: Displacement vector magnitude in X orientation (East-West) for section EW01 with isolines for all scenarios detailed in Table 7-3.

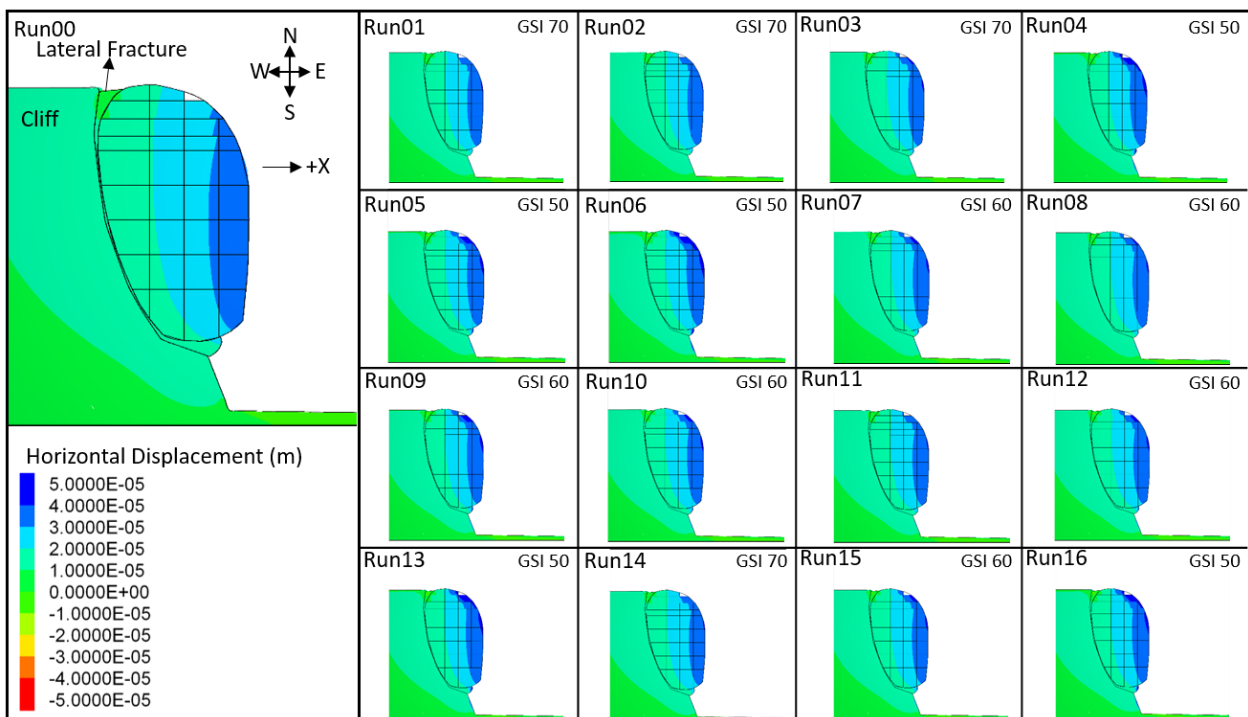


Figure 7-14: Displacement vector magnitude in X orientation (East-West) for a plan view Z02 with isolines for all scenarios detailed in Table 7-3. Note for comparison purposes, an elastic case with plastic joints is modelled as Run 00.

At the notch section, horizontal displacements in the East-West direction predominantly showcase an eastward trend, with a minor subset of zones displaying westward movements, emblematic of the intricate column-cliff-fracture interplay, as depicted in Figure 7-14. Notably, displacements proximate to the lateral fracture exhibit smaller magnitudes (averaging 0.01 mm) compared to those observed at the eastern face (0.04 mm), albeit both demonstrating positive values oriented eastwards. The influence of the joints is evidenced by the augmented displacements across joints, notably accentuating displacement on the preceding slab towards the cliff face. For instance, Joint 2 amplifies displacement in Slab 2, thereby mitigating movement behind its plane (Slab 3). However, at the southernmost edge of the rock column, numerical displacements remain consistent across all scenarios. Analogous to the East-West section, the most significant displacements occur for the lowest GSI values, with values reaching 0.05 mm for zones located at the column edge, observed in Run 06 and Run 12. Average outcomes in terms of displacement mobilization and maximum values are reported for Run 05 and Run 08, both in the highest range of stiffness but with GSI of 50 and 60, respectively.

7.3.2.2 Principal stresses

Principal stresses exhibit limited variations across different scenarios, with values shown for Run 05 in Figure 7-15. It is noteworthy that FLAC3D® adopts the convention of negative values for compression and positive values for tension. Thus, in plots created with Itasca tools, the maximum principal stress manifests as positive or close to zero, corresponding to the minimum principal stress in rock engineering convention, denoted as σ_3 . Similarly, the minimum principal stress reported by the software corresponds to the maximum principal stress for the purpose of this research, symbolized as σ_1 . Profiles encompassing north-south, east-west and plan views were compiled for both maximum (Figure 6-16a) and minimum (Figure 6-16b) principal stresses. For pure mechanical modelling, stresses are gravitationally driven.

The stress isolines remain flat at the model edges, effectively showing minimal boundary effects. Within the rock column, σ_1 is mobilized by the presence of joints, contrasting with σ_3 . At the notch section, stress mobilization is diminished owing to the presence of the lateral fracture, resulting in stress distribution between the column and the cliff. Indeed, examination of the σ_1 profile for the East-West section (Figure 7-16a) reveals isolines oriented towards the upper face of the lateral fracture, indicating stress concentration at this juncture. Furthermore, stress concentration at the toe of the rock column corresponds to maximum value for both principal stresses, reflecting the geometric configuration. Similarly, the toe of the debris layer exhibits a σ_3 of -40 kPa (in tension), suggestive of potential sliding into the KV42 tomb pit.

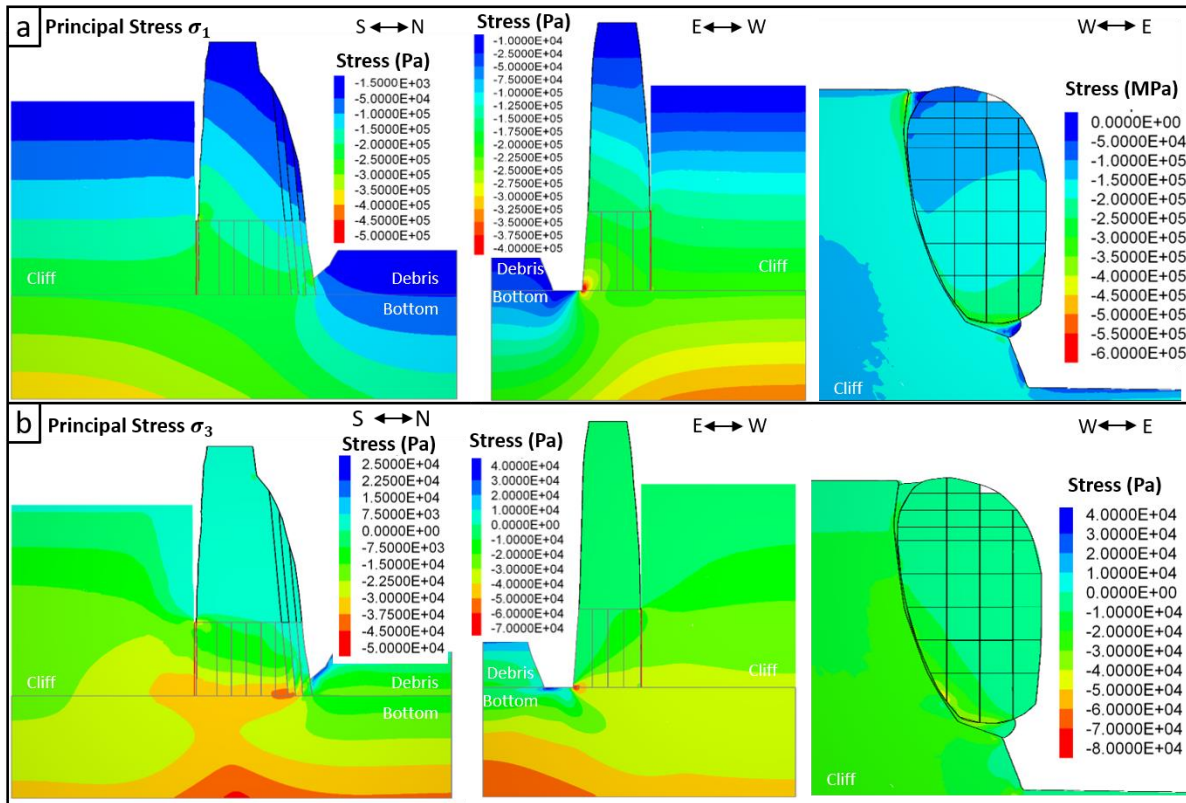


Figure 7-15: Principal stress profile for plastic model (Run 05) including a) maximum principal stress and b) minimum principal stress. Each stress profile is plotted in North-South and East-West cross sections, and plan view for elevation of 2 m.

7.3.2.3 Failure state of zones

The examination of the rock mass's strength attributes across various scenarios is depicted in Figure 7-16, focusing specifically on the east-west cross section. This illustration distinguishes two distinct types of tensile failure: "tension-p" and "tension-p tension-n". The appended suffixes "-n" and "-p" serve as markers denoting the "now" and "past" conditions respectively, offering insight into the stress calculations conducted for each cycle. A designation of "tension-p" zone state signifies an initial stress distribution surpassing the strength limit of a zone, with subsequent and more stable calculations settling stress values below the yield limit by the cycle's conclusion. Conversely, "tension-p tension-n" indicates stress values exceeding the strength limit both prior to and following cycling calculation completion. It is notable that also "now" suffixed itself denotes a failure that occurs at the end of the cycle, existing even after additional cycles are run. Shear failure could also be reported under different conditions; however, it was not seen for the mechanical modelling.

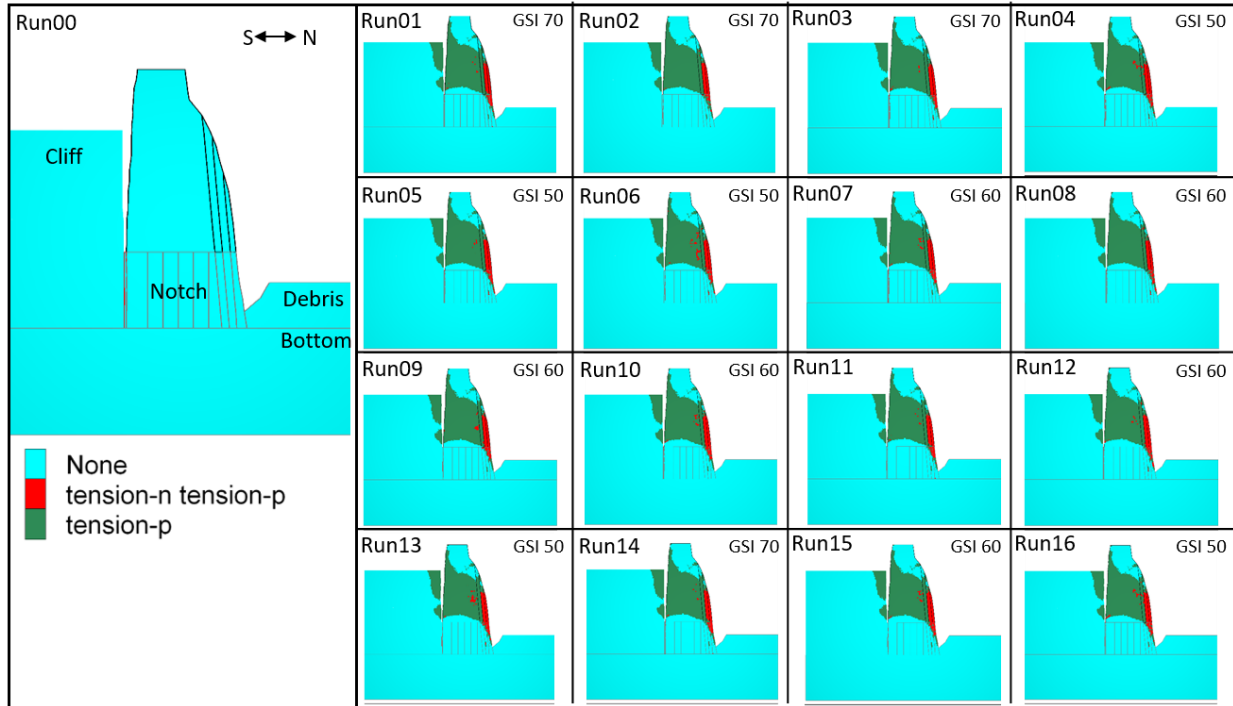


Figure 7-16: Zone state for plastic scenarios on south-north cross section, created for all scenarios detailed in Table 7-3.

The prevalence of “tension-p tension-n” failure predominantly manifests above the notch section, particularly clustering within regions of Slab 1 and Slab 2. Interestingly, Slab 3 exhibits minimal to no failed zones across most scenarios, with the exception of Run 04. However, in many cases, excluding Run 08, failed zones are dispersed behind Slab 3, aligning with locations where westward movements were recorded (as indicated in Figure 7-13). Notably, the projection onto the notch section predominantly encompasses the area preceding Joint 1, with only Run 05, Run 06 and Run 08 displaying a cluster of failed zones at the notch in Joint 2 as well. The shortest extension of failed zones in the notch section is evidenced in Run 02, which concurrently has the highest tensile strength and GSI value overall.

The spatial distribution of failed zones on the plan view at an elevation of 2 m is delineated in Figure 7-17 and shows these clustered along the outer North-East face of the notch section, extending towards the lateral fracture and the cliff. Regardless of the rock properties under consideration, all scenarios exhibit failed zones around the eroded part of Slab 1. Notably, the view indicates the extension of failed zones even beyond Joint 3, with some instances ceasing right at Joint 3 such as Run 08 and Run 13. Interestingly, the shortest extension of failed zones is observed in Run 03, failing to reach the side cliff at the forefront and reporting minimal failed zones at the lateral fracture surface.

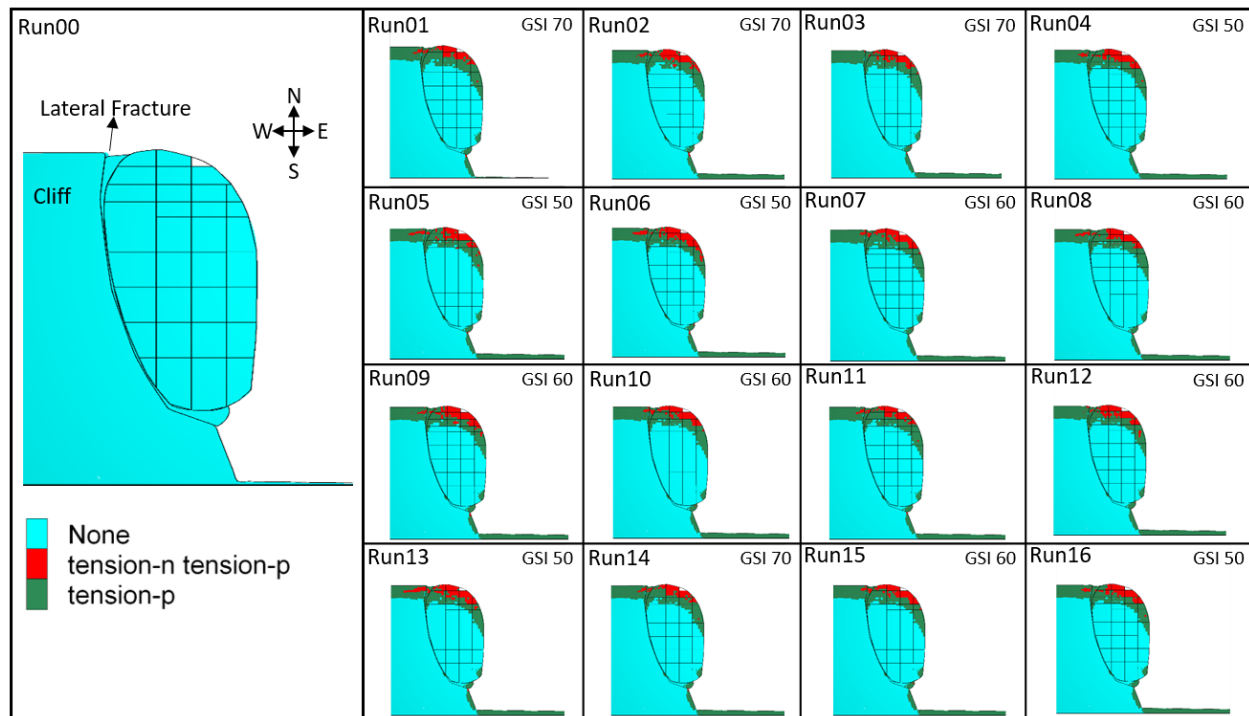


Figure 7-17: Zone state for plastic scenarios in plan view at 2 m elevation, created for all scenarios detailed in Table 7-3.

For the “tension-p” zone state, the grouping is constrained by the presence of Joint 3, though the eastern side of the notch extends this grouping following the curvature of the column. Moreover, the lateral fracture is predominantly covered by “tension-p” zones from the intersection with Joint 3 northwards. It is noteworthy that the central region of the rock column exhibits no failed or past failed zones, suggesting a degree of structural integrity in that particular area.

7.3.2.4 Joint displacements

The investigation into the normal and shear displacements of Joint 1 provides crucial insights into the mechanical behaviour of the rock mass. Figure 7-18 and Figure 7-19 delineate the spatial distribution and magnitude of these displacements. Notably, the connection of the slab generated by Joint 1 to the lateral fracture at one end underscores the significance of this joint in governing the mechanical interplay within the system. Furthermore, the analysis of shear displacements revealed predominantly positive values oriented towards the east. The recorded maximum shear displacement of 0.1 m underscores the magnitude of lateral movement occurring within the system. Notably, in scenarios with substantial displacements, such as Run 05 or Run 06, a distinct area at the center of the notch section displays larger displacements than its surroundings.

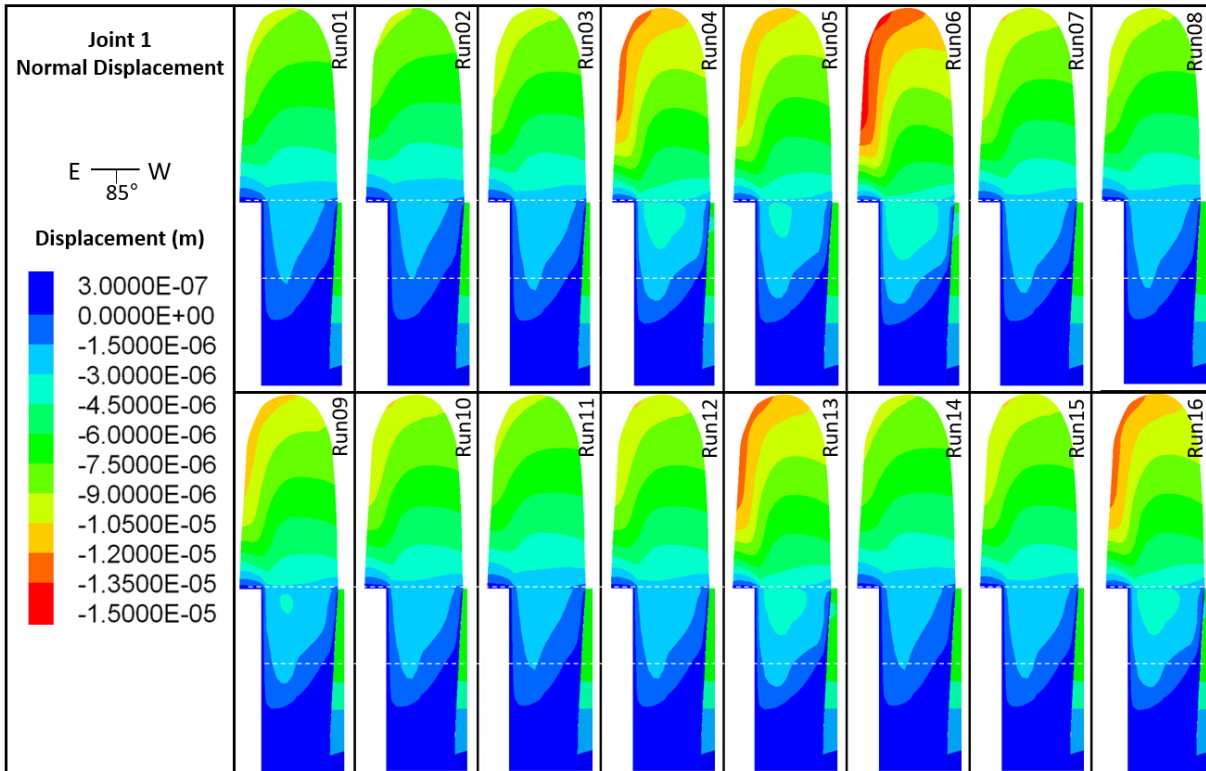


Figure 7-18: Normal displacement for Joint 1 under plastic scenarios. Properties detailed in Table 7-3. Positive displacement towards North.

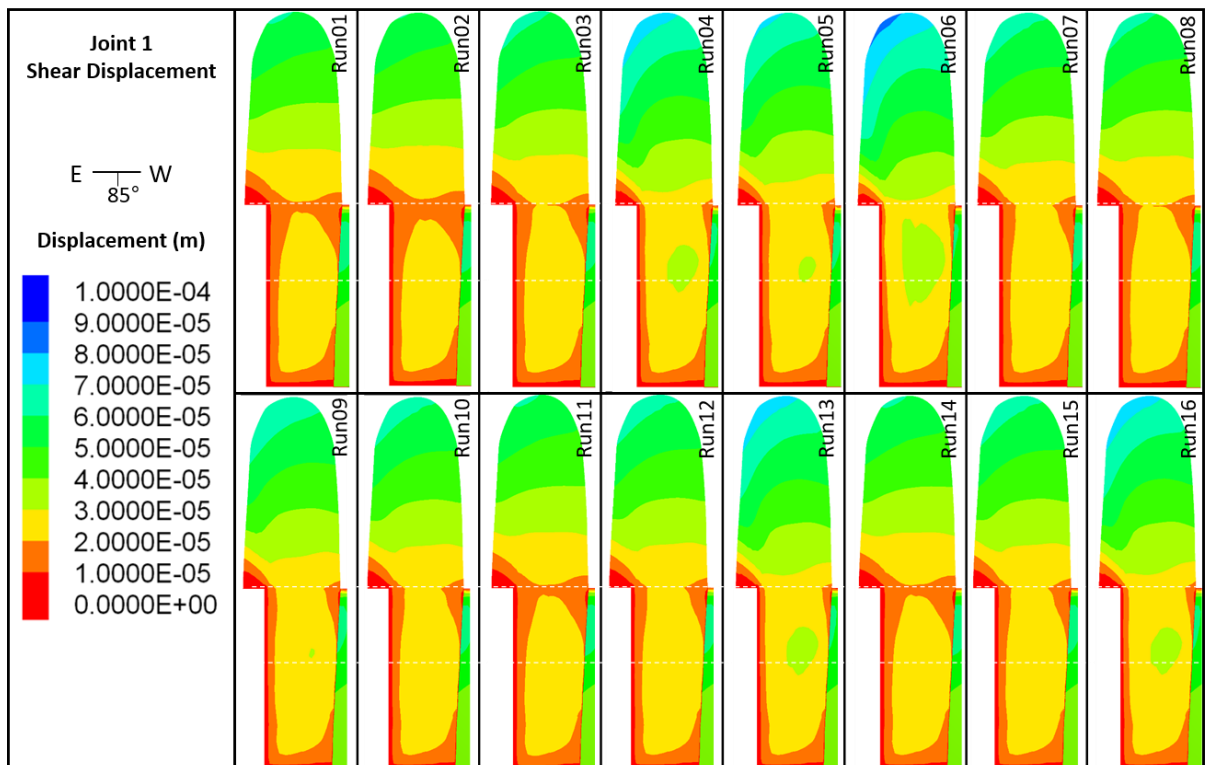


Figure 7-19: Shear displacement for Joint 1 under plastic scenarios. Properties detailed in Table 7-3. Positive displacements towards East.

7.3.3 Mechanical Simulation Sensitivity Analysis: Rock Mass Strength and Joint Testing

The stress analysis from simulation results showed small variations between runs in areas such as the rock column behind Slab 3, for both the upper part and the notch section. The lateral fracture did not have significant variations as a result of the inputs variation. Therefore, to depict the stress of the zones within these features, the results from Run05 were plotted in Figure 7-20 by group. The figure includes the failure envelope from other instances as a reference only. Stress values along the rock column and the notch border are constrained by the criteria of Run 05, indicating its status as the most conservative failure envelope in this context. For the purpose of the rock mass input parameters, the definition of conservative relies on reaching failure at smaller stress-strain tensors than other runs. Certain zone showed stresses exceeding the failure envelope, particularly within the lateral fracture group, at the southern end of the lateral fracture. These zones may have complex geometries that generate stresses beyond the strength limits.

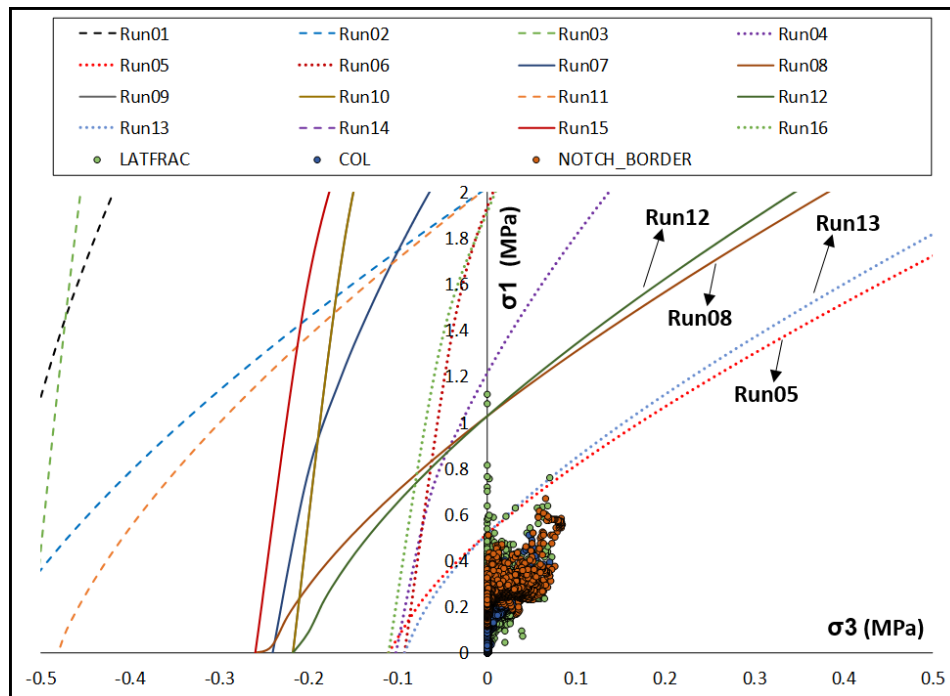


Figure 7-20: Principal stress plots with results from Run05. Failure envelopes are plotted as instances for all scenarios, with the Hoek-Brown criterion.

Although other zones in different regions may hold greater stresses, the current groups do not show an average of σ_1 above 0.5 MPa. Therefore, in order to assess the influence of joint properties on the mechanical fracturing and East-West displacements, the inputs for Run05 and Run12 were selected. Due to variations in joint properties, four new models were generated which are outlined in Table 7-4. In both base cases, normal and shear stiffness were set equally to 210 GPa/m. The other instances have smaller values and higher contrasts between normal and shear

stiffness, aiming to induce larger displacements. This approach allows for the evaluation of model stability under a weak rock mass condition leading to a subcritical state, to find the best alignment with measured data.

Table 7-4: Geotechnical properties of mechanical tests including variations in the joint stiffness values. Note: Run 05C and Run 12C are renamed as Run 17 and Run 18 after the analysis

	Property	Run 05	Run 05B	Run 05C (17)	Run 12	Run 12B	Run 12C (18)
Rock Matrix	Density (kg/m ³)		2000			2000	
	Young's modulus (GPa)		17.0			13.6	
	Poisson's ratio		0.21			0.16	
	UCS (MPa)		15.0			15.0	
	Tensile strength (MPa)		8.0			6.7	
	GSI		50			60	
Joint 1, 2, 3	Normal stiffness (GPa/m)	207	82	207	207	82	207
	Shear stiffness (GPa/m)	207	35	20.7	207	35	20.7
	Friction	35°	35°	35°	35°	35°	35°
	Dilation	30°	30°	30°	30°	30°	30°
	Tension (MPa)	0.5	0.5	0.5	0.5	0.5	0.5
	Shear-bond ratio	50	50	50	50	50	50

A comparative examination of displacements concerning Slab 1 and the resultant stresses at the lateral fracture are encapsulated within Figure 7-22, encompassing data of horizontal (East-West and North-South) and vertical displacements. The horizontal stress is exclusively delineated for East-West alignment, fluctuating between 0.025 MPa and 0.029 MPa. The minimum displacement is attained by Run 05B, registering 0.715 mm at the highest stress value of 0.029 MPa. This contrasts with Run 12B, which, despite sharing akin interface properties, achieves a higher displacement magnitude of 0.728 mm at a horizontal stress level of 0.026 MPa. Moreover, regarding displacement in the North-South direction (displacement Y), Run 05B deviates as an outlier with a displacement measurement of -0.118 mm (negative means southwards), whilst the remaining scenarios exhibit an average value of -0.145 mm (southwards).

The mean x-displacement (East-West) across all runs, spanning from Run 01 to Run 16, stands at 0.013 mm eastwards. Run 05B yields a notably lower displacement of 0.006 mm, closely mirroring the measure of Run 06 (0.007 mm). Additionally, Run 05C and Run 12C record values of 0.012 mm and 0.014 mm respectively, for a stress magnitude of 0.028 MPa, which closely aligns with the average values of east-west displacement and horizontal stress (0.026 MPa). The magnitude of displacements is driven by the vertical displacement, averaging -0.713 mm (downwards). Despite variances in interface properties, Run 12B and Run 12C yield similar displacements of 0.714 mm and 0.715 mm, respectively. Conversely, Run 05C records a displacement of -0.709 mm, falling below the average range, yet generating a heightened stress

level at the lateral fracture point, reaching 0.028 MPa. For further analysis, Run 05C is renamed as Run17; and Run12C as Run18.

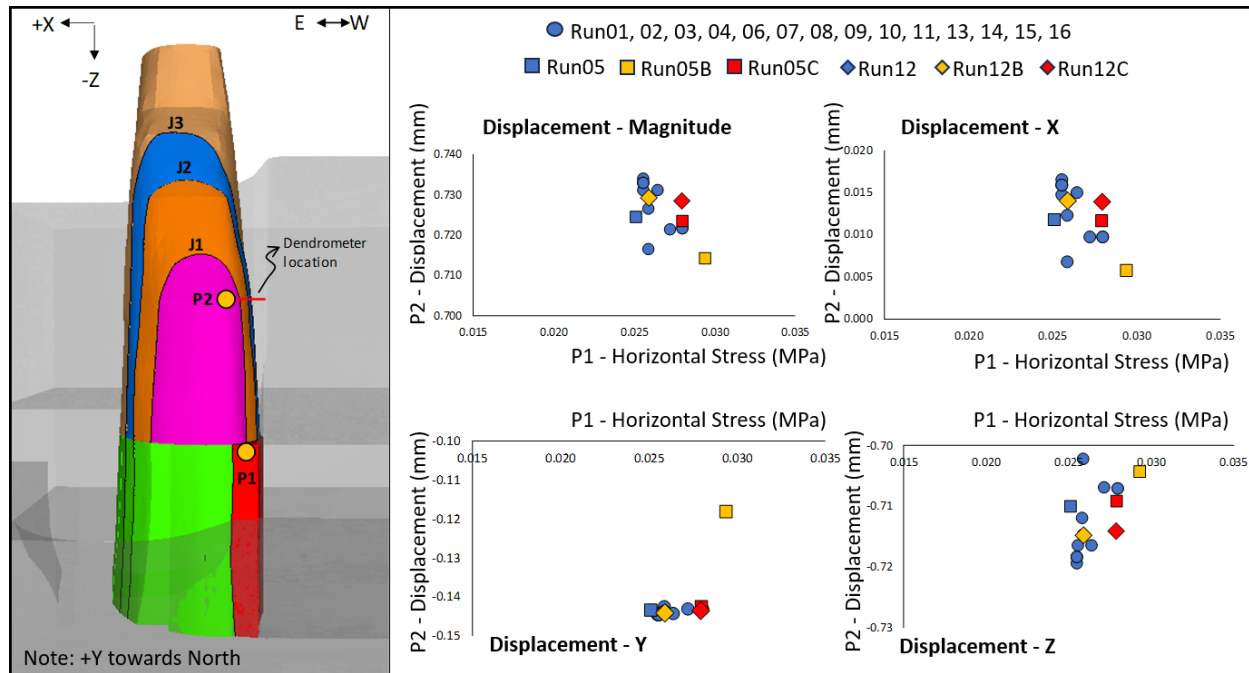


Figure 7-21: Relationship between displacements of Slab 1 (P2) and horizontal stress generated at the lateral fracture (P1), including different rock mass and interface properties. Run05C is Run17, and Run12C is Run18. It is important to note that Run 12 and Run 12B yielded numerically close results, so Run12 has been shaded out.

The plots depicted in Figure 7-22, illustrate the simulated stress from zones located at the lateral fracture and the notch section. For those zones at the notch section, the surveyed zones are located behind Slab 3 at the outer side, no deeper than 50 cm in the horizontal axis. The strength limits for Run 17 (Run05C) and Run 18 (Run12C) are also plotted. The selected rock mass properties are tailored to encompass the lowest strength values conducive to failure, particularly at the lateral fracture. Thus, one may anticipate fracture extension if other agents are assisting the stress generation, such as thermal stresses components. This is crucial for further thermo-mechanical analysis of the fracture growth. Likewise, the joint properties are calibrated to align with values tested in a two-dimensional model, thereby corroborating the analytical outcomes for both normal and shear stiffness. Additionally, numerical inputs correlate better with suggested values from Itasca (2019) and Rocscience (2020) for shear and normal stiffness calculations.

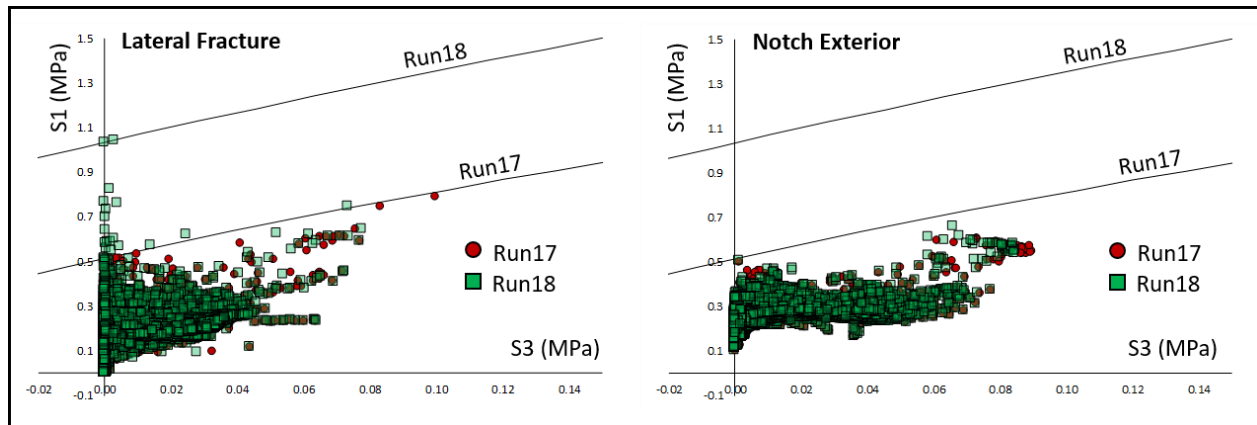


Figure 7-22: Principal stress plot including results from Run 17 (Run 05C) and Run 18 (Run 12C), for the zones allocated in the lateral fracture and the outer face of the notch section behind Slab 3 (notch exterior). Rock mass failure envelope are displayed, under Hoek-Brown criterion.

The comparison of zones states between Run 17 and Run 18 is illustrated in Figure 7-23a for the North-South cross section. Notably, failed zones in tension are predominantly concentrated within Slab 1, with a deeper extension observed down to the notch section in the results of Run 17. Additionally, Slab 2 exhibits failed zones behind Slab 1, whilst no zones fail above Slab 1. Although scarcely populated with failed zones, Slab 3 in Run 18 showcases more failed zones behind it at the central part of the rock column. However, to more accurately depict the actual condition of the column (as reported in Figure 7-1c), the results of Run 17 extend to the front of the notch, ensuring the accurate representation of the actual deterioration of the toe of Slab 1.

A plan view at a 2 m elevation is presented in Figure 7-23b, where, under the new conditions, a “shear-p tension-p” state is additionally reported. Although this new condition may be disregarded for the zone state at the end of the calculation cycle, it indicates the potential for a mixed type of failure at the front of the lateral fracture in the Run 17 scenario. Moreover, the plan view demonstrates that failure is concentrated upfront Joint 2, indicating the full integrity of Joint 2 and Joint 3, as observed on-site. The final runs, Run 17 and Run 18, are characterized by inputs with the lowest rock mass strength and the largest contrast between normal and shear stiffness.

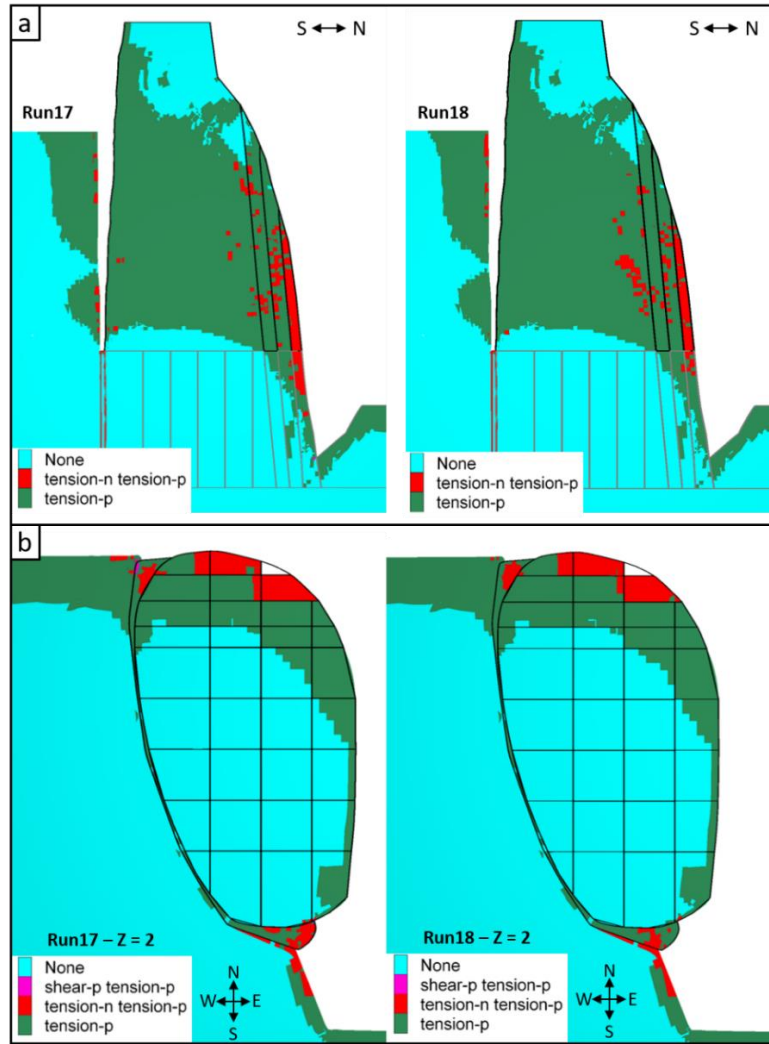


Figure 7-23: Zone state for Run 17 and Run 18, plotted for a) North-South section and b) plan view.

The careful selection of geotechnical inputs for further calculations, specifically opting for those of Run 17 (previously designated as Run 05C in Table 7-4), ensures a comprehensive exploration of the rock mass's subcritical condition. These inputs establish the lower bound for the strength of the rock mass and also provide the lowest stiffness or shearing displacements along the interfaces. These parameters not only represent the current state of the rock column but also provide a basis for studying critical areas under the lowest bounds of the failure envelope. It is notable that these inputs differ slightly from those used in the bi-dimensional model, firstly due to the Hoek-Brown constitutive model which was not tested in the bi-dimensional model. Secondly, by conducting 3D modelling, and comparing to the observations against the model scenario results, a deeper understanding of the potential rock mass properties has been developed. As such, the geotechnical inputs outlined in Table 7-5 serve as the cornerstone for the ensuing

thermo-mechanical analysis, facilitating a comprehensive understanding of the system's behaviour.

Table 7-5: Selected geotechnical inputs for mechanical FLAC3D® model of the rock column above tomb KV42.

	Property	Run 17
Rock Mass	Intact rock density (kg/m ³)	2000
	Rock mass elastic modulus (GPa)	3.94
	Rock mass bulk modulus (GPa)	2.26
	Rock mass shear modulus (GPa)	1.63
	Rock mass Tensile strength (MPa) - σ_t	0.1
	Rock mass UCS (MPa) - σ_c	0.5
	Rock mass Strength (MPa) - σ_{cm}	0.9
Joint 1, 2, 3 and Lateral Fracture ¹	Normal stiffness (GPa/m)	207
	Shear stiffness (GPa/m)	20.7
	Friction	35
	Dilation	35
	Tension (MPa)	0.5
	Shear-bond ratio	50

7.3.4 Summary of mechanical analysis findings

The created mesh was adapted to be initialized in FLAC3D®7.0 effectively for the mechanical behaviour of the rock mass, using both elastic and plastic constitutive model with joints represented as interfaces. These interfaces depicted interactions between different regions including slabs and lateral fracture. The initial stress field was set using rock mass properties from a bi-dimensional model. Plastic simulations included a sensitivity analysis of rock intact properties. Boundary conditions and initial stress settings ensured accurate results. A strategic sampling of history records across various sections, captured displacements, stresses, and zone states; facilitating detailed parametrization and stability assessment. Recorded data included principal stresses, strains, velocity and unbalanced force, amongst other variables.

Mechanical behaviour analysis across different sections revealed significant relationships between joints, the rock column and lateral fracture. Displacement patterns, especially in the rock column's upper segment and around the lateral fracture, highlighted the impact of geological features on stability. Horizontal displacements varied amongst runs, emphasizing sensitivity to rock mass properties, particularly GSI values. Principal stress analysis in the East-West sections showed the joint presence's effect on stress distribution, with concentration and mobilization at critical points like the rock column's toe and debris layer, as well as across the slabs. The spatial distribution of tensile and shear failures provided a clear representation of stress-induced damage. On the interfaces plane, normal and shear displacements at Joint 1 indicated southward

movement in the upper section of the slab, juxtaposed with the northward displacement in the lower half. This suggested a rotational mechanism operating within this plane. Such rotational behaviour could potentially influence the stability of the overall system, particularly in scenarios where significant displacements are recorded. The mechanism could also be attributed to the intricate geometric features introduced by the eroded portion of Slab 1, highlighting the interaction between structural geometry and mechanical response.

Comparative displacement and stress examination across runs with varying interface properties underscored joint stiffness's influence on mechanical response. Consistent stress values affirmed the reliability of selected rock mass properties. The final models are characterized by the lowest rock mass strength and greatest normal-shear stiffness contrast, allowing for greater joint displacements, which induce larger deformations and bring the rock mass to a critical condition for failure. The geotechnical inputs from Run 17, refined through observations and customized modelling, provided a robust basis for future thermo-mechanical analyses.

7.4 Thermal Simulations

Thermal simulations were conducted with no mechanical configuration, although the geometry, the group of zones and properties such as density were transferred from the mechanical simulations. A first set of trials aimed to adjust thermal boundaries and thermal functions, understanding the transient simulations, which were achieved after 10 different models. A second group of simulations was aimed to parametrically studied the thermal conductivity effects, by differentiating between rock and joints after five modelling instances, following the findings from Alcaíno-Olivares et al. (2023). The following sections introduce the development of the thermal transient model and the results of the ultimate simulation.

7.4.1 Thermal Settings

The thermal analysis was conducted under the assumption of isotropic thermal conduction, within a smaller region of the geometry. This thermal region comprised 1,296,797 zones, approximately 37% of the original geometry, and primarily focused on the rock column area, omitting a part of the back cliff, debris layer and bottom areas, as depicted in the plan view of Figure 7-24a. Although the non-thermal area is assigned with a null thermal model, it still permits mechanical calculations when a coupled simulation is executed. Therefore, this region is presumed to remain unaltered by thermal calculations, but subjected to mechanical perturbations resulting from temperature fluctuations within the thermal region. This simplification yields computational benefits in terms of time efficiency.

Despite the potential influence of other fractures on the thermal continuity of the rock mass, it has been postulated that long discontinuities, such as Joint 1, Joint 2 and Joint 3, play a pivotal role in guiding the thermal conduction across the labs. This hypothesis, as studied by Marmoni et al. (2020) and simulated in Alcaïno-Olivares et al. (2023), suggests that these joints constrain thermal conduction within the slabs only. To define this constraint in FLAC3D®, the region was delineated as the layer situated just behind the corresponding joint, extending across the entire plane down to the notch section, as illustrated in Figure 7-24b. Properties were uniformly assigned to all three-joint thermal regions, as detailed in Table 7-6, with distinction in thermal conductivity and thermal expansion coefficient between the rock matrix and joints. APPENDIX F includes the script for transient thermal simulations.

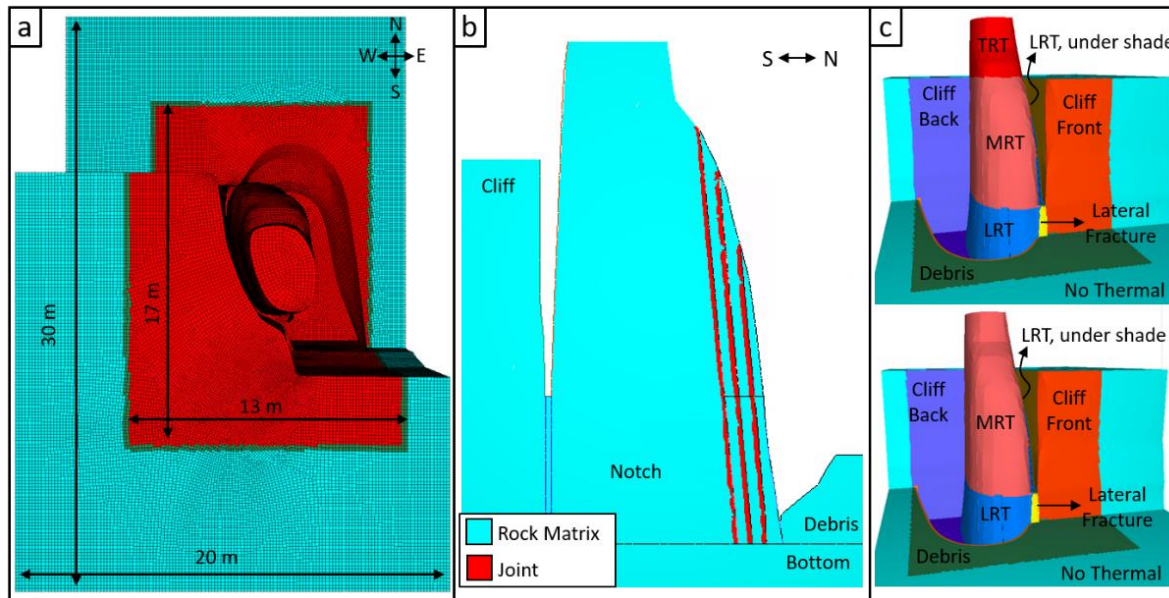


Figure 7-24: Geometry for thermal analysis with a) a trimmed region for thermal calculations which has fixed thermal boundaries to avoid geometrical influences. The model is set as thermally isotropic, however in b) area with different thermal properties for rock matrix and joints are shown, similar to Alcaïno-Olivares et al. (2023) 2D simulations. Boundaries are defined as c) varying thermal boundaries according to location for summer (top) and winter (bottom) seasonal changes, such as the regions on the rock column outer face, as well as the cliff, debris, lateral fracture and the region in between the rock column and the cliff as observed through Infrared Thermographic images, as detailed in Alcaïno-Olivares et al. (2023).

Table 7-6: Thermal properties for rock matrix and joints.

Property	Rock matrix	Discontinuities
Thermal conductivity (W/mK)	7.5×10^{-1}	7.5×10^{-3}
Heat capacity (J/kgK)	750	750
Expansion coefficient (1/K)	8×10^{-6}	8×10^{-7}

The thermal boundaries within the designated thermal region are depicted in Figure 7-24c. Given the area's morphology and the varying incidence angles of the sun path between winter and summer, as discussed in Section 6.5.2 based on Alcaïno-Olivares et al (2023) and illustrated in

Figure 6-5, the dynamism of these boundaries is contingent upon location and numerical values for assigning surficial temperatures. Consequently, three distinct regions – low region temperature (LRT), middle region temperature (MRT), and top region temperature (TRT) – are designated as sinusoidal functions with parameters calculated using the Bentz model (2000), as detailed in Section 6.6.3 for the bi-dimensional model. However, the formulation of these functions is adapted for the three-dimensional scenario, with refinements based on additional on-site data. Figure 7-25 provides a summary of the thermal functions for each region, with particular emphasis on the changes in amplitude for the idle region temperature with different months, reflecting variations in sun radiation due to shade patterns in the study area.

These thermal functions are implemented in FLAC3D® following the framework outlined in Equation 7-1, utilizing the input “thermal time total” to vary temperature values on the surface boundaries. The thermal time total represents the accumulated thermal time after every cycle in the thermal analysis, encompassing heating, cooling, or any other changes over the duration of the thermal simulation.

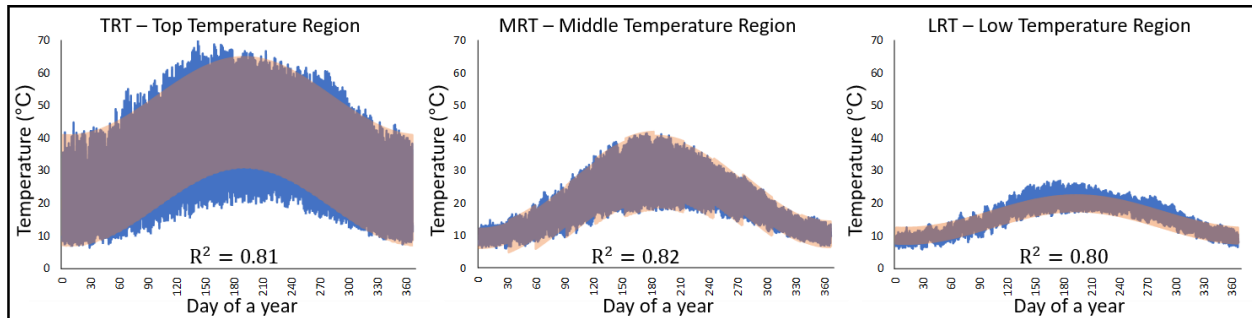


Figure 7-25: Thermal functions assigned to each thermal boundary, such as top region, middle region and low region, throughout a year time. Middle region temperature function has variable inputs to represent the sun radiation changes in the area.

$$Temp = A * \left(\sin \left(2 * \pi * \frac{thermal.time.total}{24 * 365 * 3600} \right) + B + C \right) + a * \left(\sin \left(2 * \pi * \frac{thermal.time.total}{24 * 3600} \right) + b + c \right) \quad \text{Equation 7-1}$$

Indeed, despite the thermal functions being uniformly defined, their distinctions lie in the parameters that govern their behaviour. While A, B and C dictate the functions' variations over the course of a year, representing seasonal changes, the parameters a, b and c are for the expected daily variations. This differentiation elucidates the disparities between the regions shown in Figure 7-25 and underscores the rationale behind the diverse definitions for the middle region temperature functions detailed in Table 7-7. Specifically, the MRT function exhibits varying daily

fluctuation within a narrow range during cooler months like November to February, whereas the range expands during hotter months such as May, June or July, reflecting the seasonal temperature dynamics characteristics of the study area.

Table 7-7: Temperature function parameters for each thermal boundary.

Temperature Function	A	B	C	a	b	c
TRT	12	1.70	3.0	17	2	0.00
LRT	5	1.75	3.0	2.5	2	0.00
MRT	14	1.60	1.40			
MRT01 – January				3	2	1.20
MRT02 – February				5	2	0.50
MRT03 – March				6	2	0.00
MRT04 – April				8	2	-0.20
MRT05 – May				10	2	-0.25
MRT06 – June				12	2	-0.30
MRT07 – July				11	2	-0.35
MRT08 – August				9	2	-0.30
MRT09 – September				7	2	0.00
MRT10 – October				6	2	0.50
MRT11 – November				4	2	1.10
MRT12 – December				4	2	1.20

To incorporate the dynamism of the thermal boundaries into the modelling, specific thermal boundary conditions have been assigned to each month in a calendar year. These conditions not only alter numerical inputs but also adjust the locations of these boundaries, as illustrated in Figure 7-24c for winter and summer months. Following the completion of each simulated month, the boundary conditions are reset, and new conditions are applied for the subsequent month. To implement this sequencing, the thermal time total acts as the accumulated time being calculated from an initial time set to zero, for example, January 1st 2018 at 00:00. As an illustration, if one considers the transition from January to February, the thermal time total at the end of January is 2,678,400 seconds. To set the simulation stage for February 28th 2018 at 23:59, the thermal time total gained during January is added to the number of seconds within February, so the thermal time total results in 5,097,600 seconds to move to the next month, to March 1st 2018 00:00. This process continues for each subsequent month, ensuring the accurate sequencing of the simulation stages.

The outer thermal boundaries were set at a constant temperature of 15°C, consistent with the initial model temperature. The implicit mode was employed, with a fixed thermal step of 150 seconds. During winter conditions, all boundaries outside the rock column were assigned the low temperature region function, whilst in summer, the debris, pit bottom, and the front of the lateral

fracture were switched to the middle temperature region function. Temperature histories were generated for the same locations outlined in Section 7.3.1.

7.4.2 Thermal Model Results

Thermal results were retrieved as time series of rock surface temperatures at different locations as introduced in Figure 7-26. Although the thermal sensor's location aligns with the surveyed point 3305, four linear surveys were added to compare the average value against real measurements, ensuring a more robust analysis. Data were compared for the timeline between April 2018 and July 2023, including the most updated measured data.

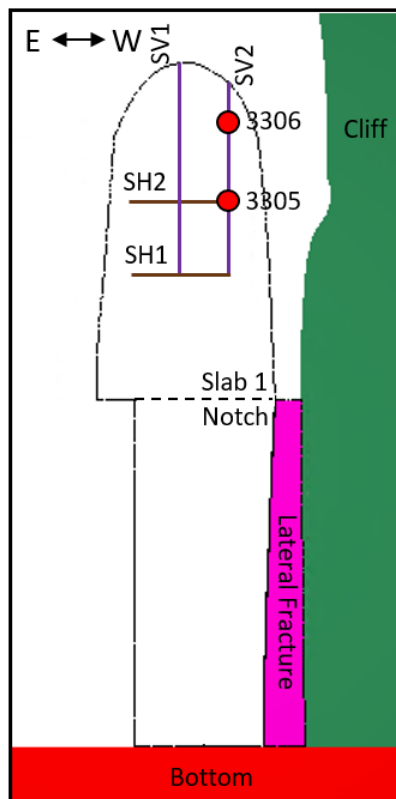


Figure 7-26: Slab 1 cross section portraying the surveyed points (3306, 3305), the vertical surveys (SV1, SV2) and the horizontal surveys (SH1, SH2). Lateral fracture, cliff and bottom are shown as relative features to provide morphological context, yet all data are measured on Slab 1.

7.4.2.1 Time-series comparison

The measured rock surface temperature data are introduced in Figure 7-2d, showing the missing data due to connectivity and maintenance of the monitoring system. The information was completed with the use of environmental parameters as detailed in Section 6.6.1, following Alcaïno-Olivares et al. (2023) methodology. The integrated rock surface data is named as Series, used for comparison purposes to the simulated results. Figure 7-27 compiles a group of time-

series and scatter plots at different locations shown in Figure 7-26. Pearson correlation factors (R^2) between series and simulated results were above 0.9. The simulations focus on the alignment at warm temperatures to ensure that thermal stresses were properly inputted in the higher range of deformation during further thermo-mechanical simulations. During warmer months, such as June through August, all surveys matched the average trend of rock surface temperature series, with average peaks between 40°C and 45°C. Conversely, at the colder range, the modelling setting and the inputted functions delivered larger variations, such as between October and January, with simulated values being up to 5°C colder than the series data in a range of 8°C to 12°C. However, the yearly trends show a cyclic variation with no accumulation or loss in temperature reflecting the capability of the model to dissipate the heat accordingly.

The survey point RT-3306 has a correlation factor of 0.916 for the entire simulation time, fitting the measured data with an R^2 of 0.961 during the first simulated year, from April 2018 to April 2019. Since RT-3306 is close to the edge of Slab 1, it is more strongly influenced by the boundary conditions due to the thermal function inputs, compared to RT-3305, which explains the hourly fluctuation effect. Results from RT-3305 reached a maximum peak temperature of 40°C, which is 4°C colder than the observed values. The simulated trend for RT-3305 is minimally influenced by the boundary conditions, similar to SH1. As mentioned earlier, SH1 represents the average of three points along the linear survey, resulting in a similar trend to RT-3305, yet with a higher R^2 of 0.918 and temperatures ranged between 9°C and 42°C. The linear horizontal survey SH2 shows the influence of the boundary conditions related to the proximity of the Slab 1 edge by comparing the hourly fluctuation to the SH1 results. The SH2 aligns with an R^2 of 0.927 with the observed data. Temperatures for SH2 range between 5°C and 45°C, with differences of up to 8°C during the colder months. The linear vertical surveys SV1 and SV2 have R^2 values of 0.918 and 0.917, respectively, with similar peak values of 8°C and 42°C for the coolest and hottest temperatures.

A further analysis was conducted using the calculated trend of measured data, referred to as Calculated, which represents the average trend of the rock surface time-series. By using the average trend, hourly fluctuations smoothed, allowing for a focus on annual trends and seasonal variations. As shown in Figure 7-29, the resulting correlation factor across all surveyed points and lines was on average 0.97. The hottest temperature ranges for both calculated and simulated trends match, but the peak values in the simulated results were reached approximately 20 days earlier than in the calculated time-series. The same lag is observed for the coolest temperatures, and this lag remains consistent throughout the entire simulation period.

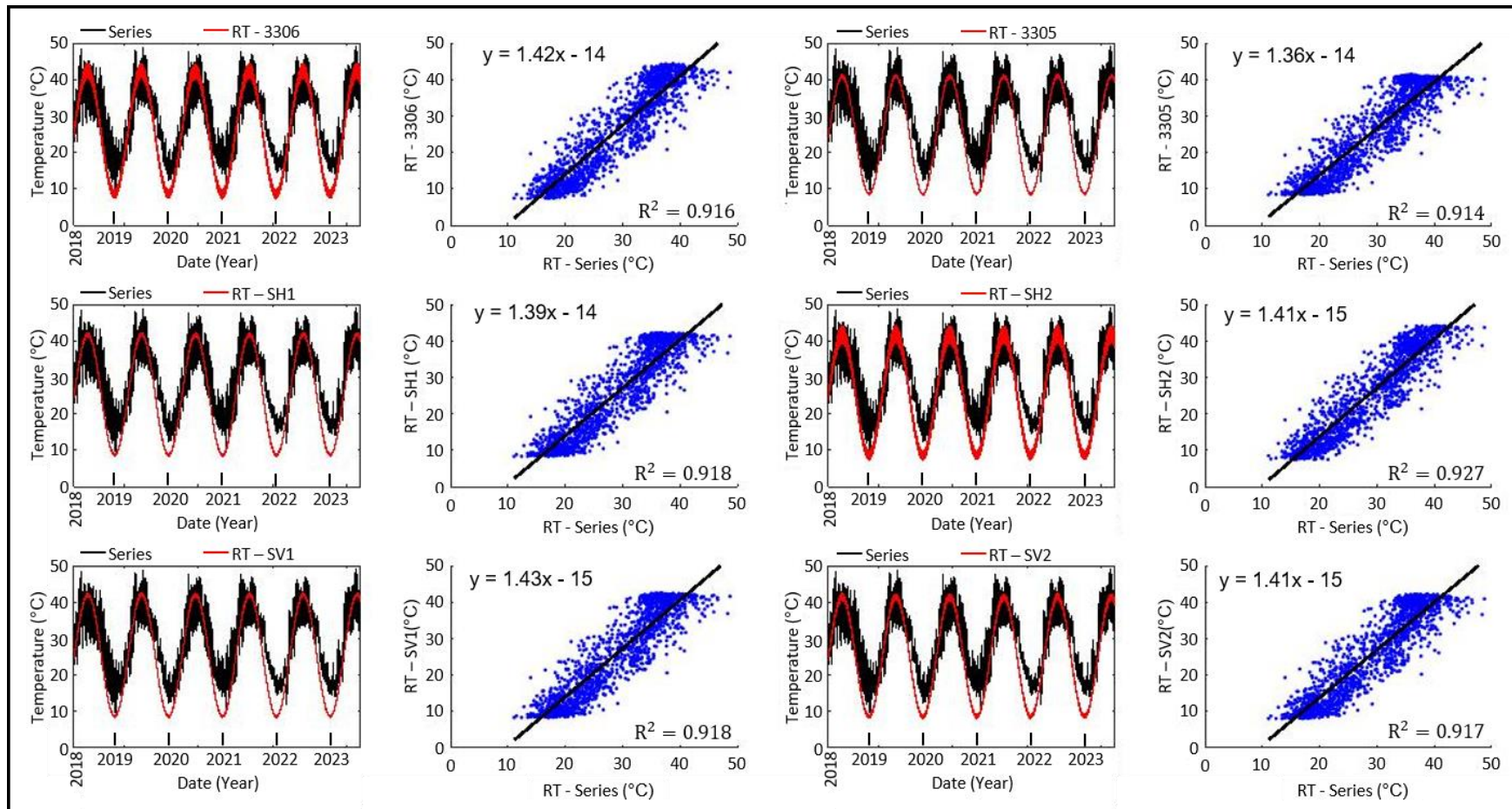


Figure 7-27: Time series comparison for rock surface temperature measurements (Series) and simulated results retrieved from the thermal model at several locations as introduced in Figure 7-26.

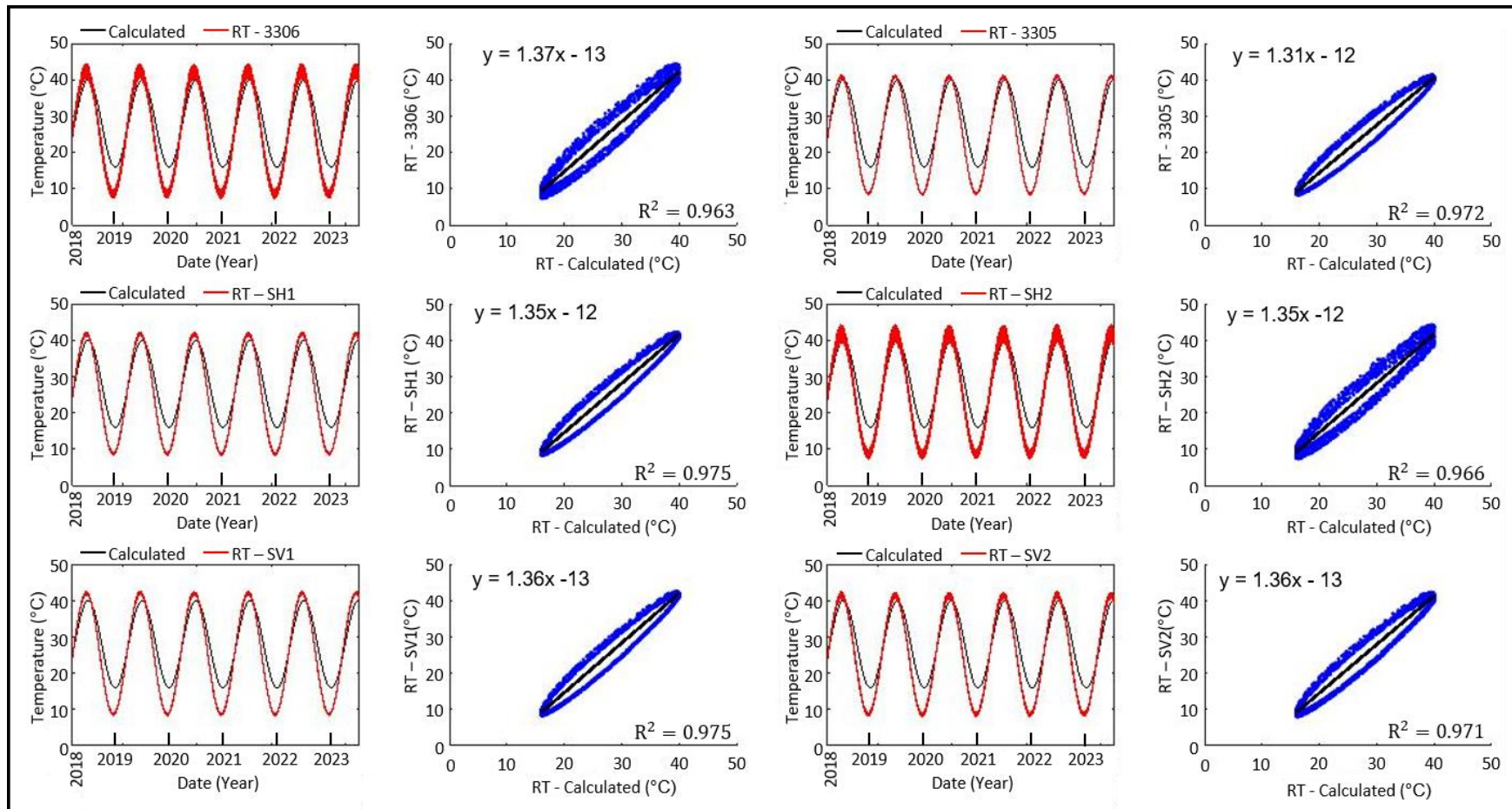


Figure 7-28: Average trend of rock surface time-series compared to simulated thermal model results retrieved at several locations as introduced in Figure 7-26.

In each cycle, the differences between the decreasing trend and the calculated rock temperature are larger, whereas the trends converge more closely on the increasing trend for the same temperature ranges. This is more evident in the annual shape of the scatter plots around the linear relationship across all surveys. The survey at RT-3305 shows a R^2 of 0.972, although the difference between peak values at the coolest range is 7°C. Both the linear horizontal survey SH1 and the vertical survey SV1 have an R^2 of 0.975, which is the highest amongst the surveys and neither intersects with RT-3305. However, unlike RT-3305, both linear surveys show peak values that are 3°C hotter than the calculated data.

7.4.2.2 North-South temperature profile

Temperature profiles were generated for both North-South cross section and the East-West slice of Slab 1, with data extracted along linear surveys. The North-South section comprises four horizontal and four vertical surveys (Figure 7-29a), designed to traverse the slabs and the rock column behind Slab 3. Temperature readings for July 2018 indicate a transition between Slab 1 and Slab 2, influenced by the thermal properties of Joint 1. This results in the highest temperatures (exceeding 40°C) being concentrated in Slab 1 before Joint 1. Behind Joint 1, in Slab 2, temperatures ranged from 20°C to 35°C, except above the upper end of Slab 1. At the notch section, external fluctuations impact all three slabs, but the area behind Joint 3 remains at a steady 15°C, as determined by the initial model temperature. A vertical survey within Slab 1 (Figure 7-29b), labelled CX2Y1, reveals significant seasonal variations of 5°C to 50°C above 2 m, near the notch section limit, whilst below this elevation, temperatures range between 10°C to 30°C.

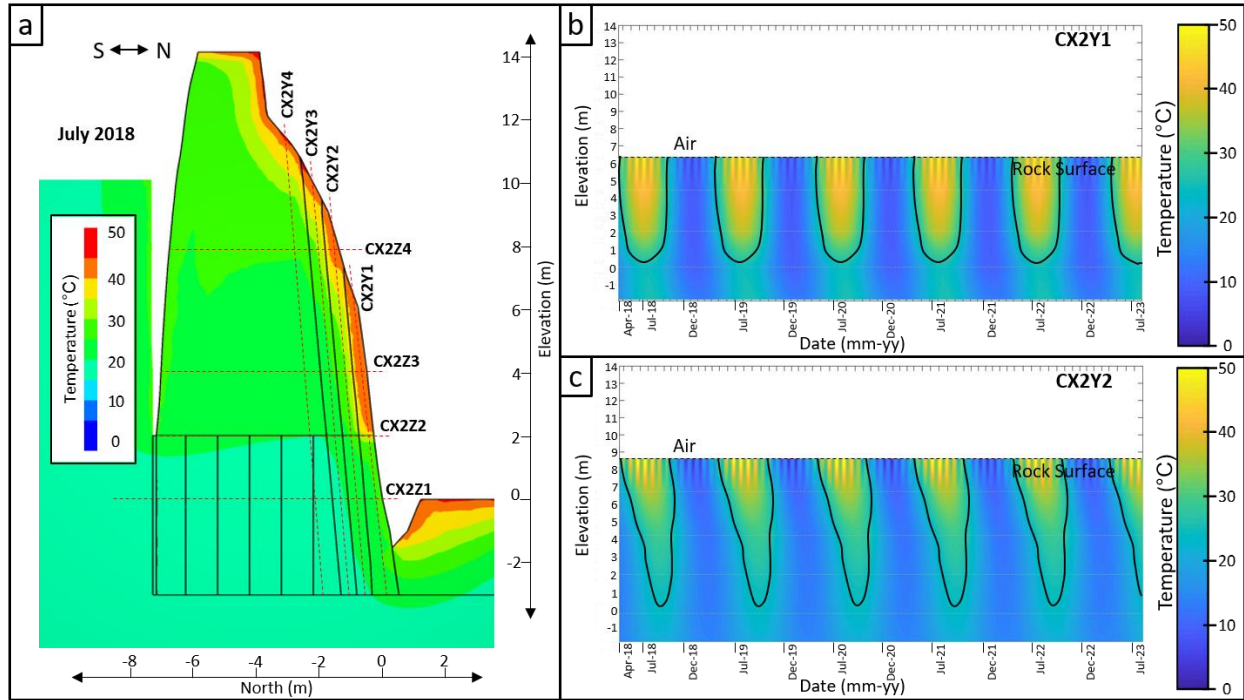


Figure 7-29: Temperature distribution on a North-South cross section, highlighting a) a set of subvertical and horizontal linear surveys conducted across the slabs and rock column on a temperature profile for July 2018. Surveys were reported as time-series in b) maps of temperature with vertical distance for CX2Y1 survey, crossing Slab 1, and c) CX2Y2 which shows Slab 2 data. Black contour lines enclose temperatures above 25°C.

In Slab 2, as illustrated in Figure 7-29c by survey CX2Y2, temperature fluctuations are predominantly observed above 7 m of elevation, aligning with the upper end of Slab 1. Between 2 m and 7 m, temperatures ranged from 5°C to 35°C, whilst below 2 m at the notch section, this range narrows to 5°C to 20°C. The temperature range in Slab 2 is narrower than in Slab 1, attributable to the lower thermal conductivity within Joint 1 and the impact of thermal boundary conditions.

This is demonstrated in Figure 7-30a and charted in Figure 7-30b for the CX2Y3 survey. Similar to the other slabs, temperatures at the notch section fluctuate between 5°C to 20°C. However, between 2 m and 9 m, the temperature ranged from 15°C to 30°C. The temperature distribution profile in Figure 7-30a for April 2019 shows that the influence of boundary temperatures extends only to Slab 2, whilst Slab 3 and the remaining rock column remain constant at 15°C at the notch section and at elevations above the central part, such as 4 m. Due to the column's geometry, the survey behind Joint 3, identified as CX2Y4 in Figure 7-30c, indicates a 2 m length for temperature fluctuations at the upper end. Seasonal variations ranged between 5°C to 25°C, with a maximum value of 20°C at the notch section. The fluctuation range is shorter than those observed within the slabs due to the survey's location and the minimal effect of environmental variations.

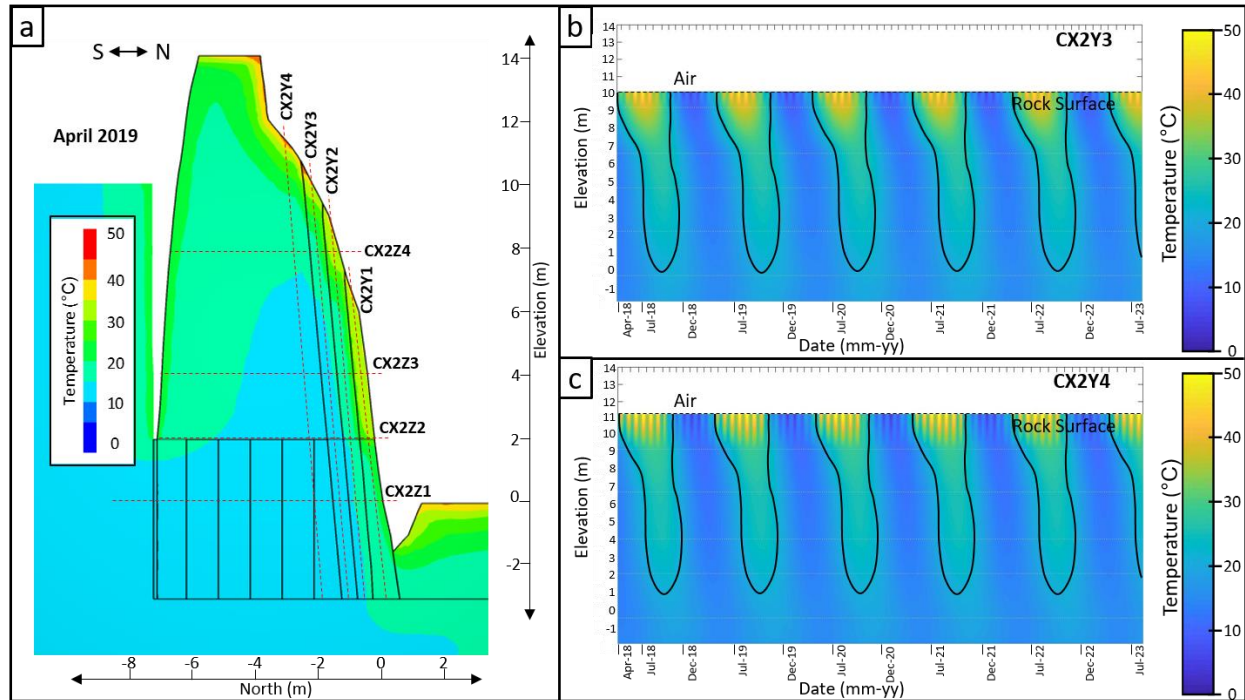


Figure 7-30: Temperature distribution on a North-South cross section, highlighting a) a set of subvertical and horizontal linear surveys conducted across the slabs and rock column on a temperature profile for April 2019. Surveys were reported as time-series in b) maps of temperature with vertical distance for CX2Y3 survey, crossing Slab 3, and c) CX2Y4 which shows the data for rock column behind Joint 3. Black contour lines enclose temperatures above 20°C.

Horizontal linear surveys from Figure 7-30a are designed to illustrate the temperature distribution across several slabs, emphasizing the effect of the thermal conductivity contrasts between intact rock and joints. These linear surveys are presented in Figure 7-31 as colour maps, with the north distance on the y-axis corresponding to the north axis of Figure 7-31a. Linear survey CX2Z1 (Figure 7-31a) is situated at the mid-height of the notch section and is the only survey that extends beyond the rock column to cross the lateral fracture, ending at the adjacent rock cliff. Temperature values for CX2Z1 ranged between 5°C to 20°C at the edge of the rock mass, with significant variation at a north distance of -0.5 m, where Joint 1 is located.

Similar disruptions are observed at distances where Joint 2 and Joint 3 are located, while surveyed points further south report a more continuous temperature distribution. Similarly, survey CX2Z2 (Figure 7-31b), positioned at the boundary between the slabs and the notch section, recorded temperature values between 5°C to 40°C, with the highest temperatures concentrated within Slab 1. Slab 2 and Slab 3 hold temperatures ranging from 5°C and 40°C, with similar temperature contrasts between the upper part of the rock column and the notch section. The southern end of the survey recorded cooler values during winter months compared to the northern surveyed nodes, with temperatures dropping below 5°C. It is worth noting that although survey CX2Z2

extends to the lateral fracture, the ending surveyed node is not in contact with a free surface that could cause boundary effects.

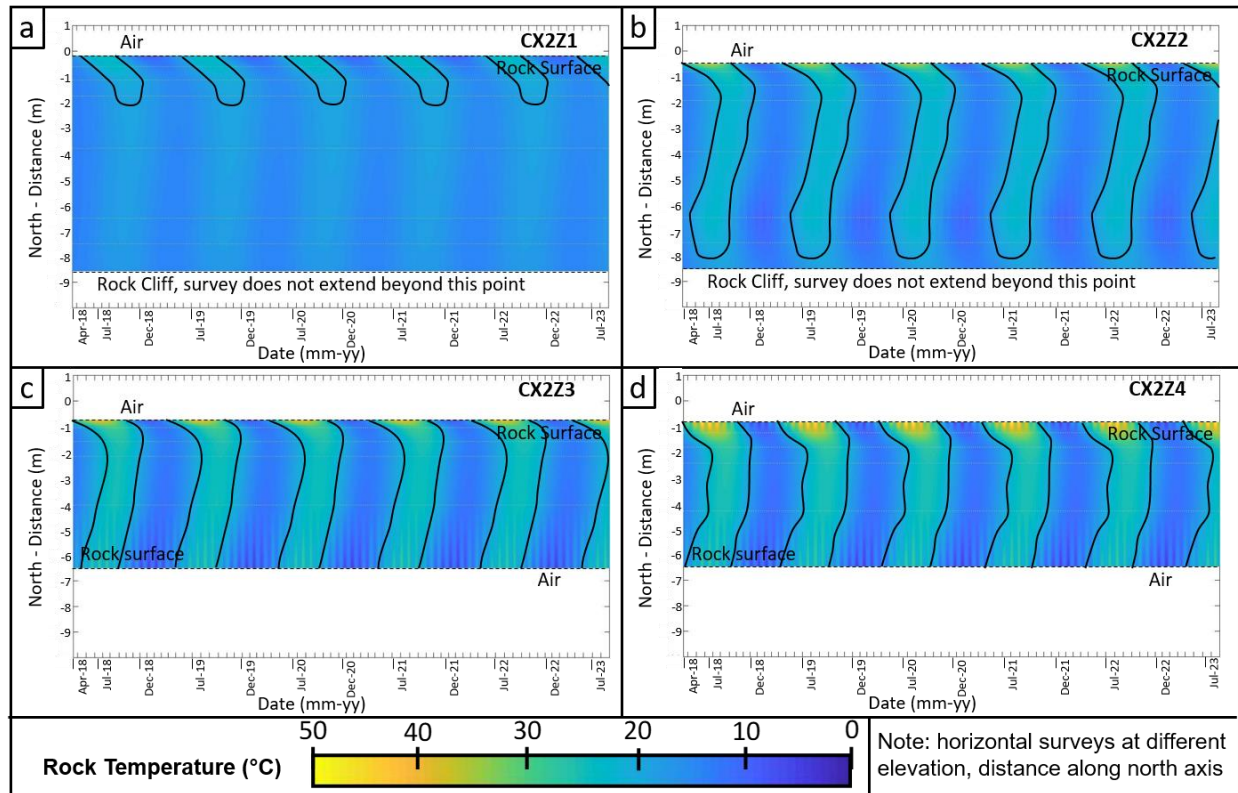


Figure 7-31: Horizontal linear surveys as time-series shown on temperature maps, referred to Figure 7-29 and Figure 7-30, at different elevations such as a) CX2Z1, current ground level; b) CX2Z2, limit to notch section; c) mid elevation on Slab 1, CX2Z3; and d) above Slab 1 to cross Slab 2 and Slab 2 only, CX2Z4. Vertical axis corresponds to horizontal distance. Black contour lines enclose temperatures above 20°C

At the upper part of the rock column, survey CX2Z3 intersects the mid-height of Slab 1, extending from the edge of Slab 1 to the back of the column which is exposed to the air, as depicted in Figure 7-30a. Shown in Figure 7-31c, temperature values at the northern edge ranged from 5°C to 50°C. The presence of joints is indicated by disruptions in the temperature distribution with depth into the rock column. Additionally, the influence of boundary conditions at the southern end resulted in temperature variations from 5°C to 35°C, consistent with the boundary conditions set for the region between the rock column and the adjacent cliff. A more extensive influence is observed across survey CX2Z4, reflecting data from the upper part of Slab 2, unaffected by the boundary of Slab 1. Illustrated in Figure 7-31d, the temperature fluctuated in Slab 2 and ranged from 0°C to 50°C, which is broader than those observed in Slab 1. Temperature disruptions occur at Joint 2 and Joint 3, with average temperatures of 30°C in summer and 10°C in winter. The southern end is

also influenced by thermal boundary conditions, where temperatures ranged from 5°C to 35°C, as seen in survey CX2Z3 (Figure 7-31c).

7.4.2.3 East-West temperature profile

Horizontal and vertical linear surveys were also conducted for the East-West profile of Slab 1, as shown in Figure 7-32a, to capture the temperature distribution in the upper part of the rock column and at the notch section. For instance, in July 2018, the temperature at the eastern edge of Slab 1 was 40°C, whilst the western end, near the lateral fracture, remained cooler at 30°C. The central part transitions within a range of 30°C to 40°C, influenced by both thermal boundaries. However, the notch section is cooler, with temperatures between 20°C and 30°C, due to the lower boundary inputs. Vertical survey J1X1, illustrated in Figure 7-32b, shows a colour map of temperatures throughout the entire simulation period, with the y-axis corresponding to model elevation shown in Figure 7-32a.

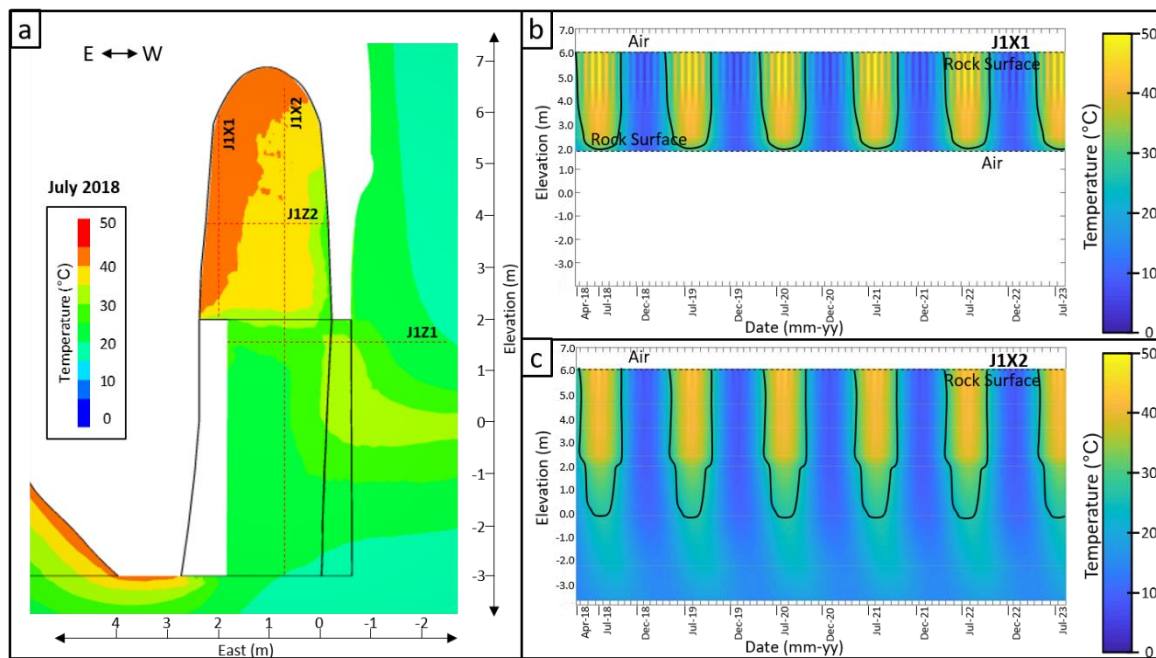


Figure 7-32: Temperature distribution on an East-West cross section of Slab 1, highlighting a) a set of subvertical and horizontal linear surveys for temperature on Slab 1 for July 2018. Surveys were reported as time-series in b) maps of temperature with vertical distance for J1X1 survey, and c) J1X2 survey. Black contour lines enclose temperatures above 30°C

The influence of temperature inputs is observed by the seasonal temperature contrasts, ranging from 5°C in winter to 45°C in summer. The bottom of survey J1X1, acting as a free end, has a temperature in the colder range, influenced by shade patterns on the rock mass, and contact with the notch section, which remains at lower temperatures. The survey J1X2, shown in Figure 7-32, has a smoother temperature transition between values than J1X1, due to the distance from the

edge of Slab 1, with low temperatures at the notch section ranging from 5°C in winter and 25°C in summer, and dissipating at depth.

A temperature profile for the colder months, such as April 2019, is shown in Figure 7-33a, with overall values ranging from 20°C to 35°C in the upper part of Slab 1. A horizontal survey at the notch section, called J1Z1 and illustrated in Figure 7-33b, extends from the eastern end to the adjacent cliff, crossing the lateral fracture. The elevation of this survey is close to the boundary between the notch and the upper part of Slab 1, so temperatures are influenced by multiple boundary inputs. For instance, in summer, the average temperature at the eastern edge is 30°C, whereas at an East-distance of 1 m (distance referred to vertical axis in Figure 7-33b), the temperature is close to 40°C. Temperature tends to decrease westwards, with fluctuations influenced by the thermal inputs from the lateral fracture location, stabilizing around 20°C at the adjacent cliff by the end of the survey. Conversely, survey J1Z2 at 4 m elevation, which is on Slab 1 and illustrated in Figure 7-33c, shows a continuous temperature transition from 40°C in summer at the eastern edge to 20°C at the western side of Slab 1, influenced by out-of-plane boundaries.

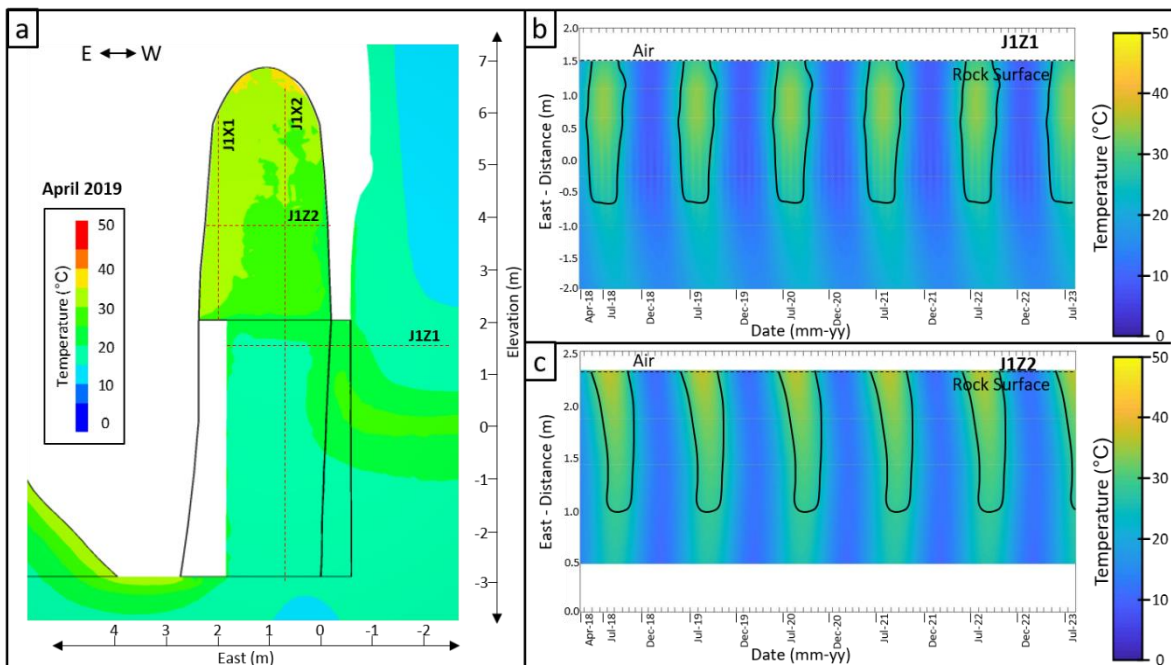


Figure 7-33: Temperature distribution on an East-West cross section of Slab 1, highlighting a) a set of subvertical and horizontal linear temperature profiles on Slab 1 for April 2019. Surveys were reported as time-series in b) maps of temperature with horizontal distance for J1Z1 survey, and c) J1Z2 survey. Black contour lines enclose temperatures above 30°C

7.4.3 Summary of thermal analysis findings

The thermal settings considered isotropic thermal conduction, with variations for thermal conductivity between rock and joints. The thermal boundaries were dynamically adjusted based on the observed seasonal changes and sun's incidence angles, with distinct regions designated as low, middle and top temperature regions. These boundaries were modelled using sinusoidal functions adapted for three-dimensional scenarios. The thermal results indicated significant seasonal and spatial variations, with temperatures influenced by joint properties, boundary conditions and environmental factors.

The results from simulations demonstrated a high correlation with measured and calculated data collected on-site, with R^2 consistently above 0.9 across various surveyed point and linear profiles, surrounding the temperature sensor placed in the rock mass. Despite minor discrepancies observed during colder months, the agreement validates the efficacy of the thermal modelling approach employed in capturing real-world thermal behaviours within the rock mass at the KV42 cliff site. Temperature profiles generated for both North-South and East-West cross sections provided insights into the temperature distribution, particularly to assess the thermal conduction across joints. Similar to the bi-dimensional analysis from Section 6.7.1, the thermal results revealed notable temperature disruptions across the slabs due to the presence of joints, illustrated in North-South sections. Linear surveys, plotted on colour maps, show the temperature distribution with spatial and temporal variations. For Slab 1, the temperature is influenced by the upper part and the notch section contrasts, as well as by the influence of temperature variations at the lateral fracture.

Overall, the resulting rock mass temperature follows the boundary settings in terms of magnitude and location, and the temperatures correlate with measured data. Hence, thermal settings, along with mechanical observations, can be used in the subsequent thermo-mechanical model to simulate displacements resulting from thermal fluctuations.

7.5 Thermo-mechanical Simulation

A coupled mechanical and thermal transient model was implemented to obtain the time-series of rock mass response for displacements of Slab 1, aiming to match the measured data for fracture opening. The goal is to generate fluctuating thermal stresses that follow the temperature cycles, which will induce different stability states in the rock mass and potentially lead to reaching strength limits. Amongst all thermal inputs, the thermal expansion coefficient is crucial for the coupled thermo-mechanical solutions so tests on this input are required. Nevertheless, in purely thermal solutions, thermal properties such as thermal conductivity, density and the heat capacity of rocks are relevant. Therefore, in the thermo-mechanical solution, it is essential to use similar thermal properties similar to those used in the thermal analysis to ensure consistency with the previously discussed results.

7.5.1 Thermo-mechanical calibration

Thermo-mechanical simulations were performed using the rock mechanical properties from Table 7-5 and the thermal properties from Table 7-6. Nevertheless, some modifications were required to align the measured displacements of Slab 1 with the simulations. Consequently, initial trials employed an elastic Hoek-Brown constitutive model, with subsequent iterations incorporating interfaces and varying properties to identify the parameters that resulted in the best trend that corresponds to the measured displacements. Interface properties, including plasticity, were also varied to examine the peaks and waveforms of the retrieved time-series. To achieve temperatures akin to those previously discussed in the thermal analysis, the thermal conductivity of the rock and thermal joints were set with a difference of two orders of magnitude: the rock value was 7.5×10^{-1} (W/m^{°K}) and the conductivity of all the joints was 7.5×10^{-3} (W/m^{°K}). For both rock and joints, the heat capacity was 750 (J/kg^{°K}). Nonetheless, the thermal expansion coefficient was adjusted on a case-by-case basis to determine the optimal value that could help align the trend across all simulations with the measured data. The thermal expansion coefficient is crucial in linking temperature fluctuations with the resulting mechanical displacements. Table 6-7 presents the input parameters for the 14 elastic simulations, which primarily focused on interface properties with different stiffness and strength. Thermo-mechanical models are simulated in FLAC3D® by integrating the mechanical and thermal analysis, as scripted in APPENDIX G.

Table 7-8: Mechanical and thermal properties of interfaces for thermo-mechanical simulations. Runs 100, 101 and 102 do not have interfaces explicitly set. ¹SBR: shear-bond ratio is an artificial value that defines the ratio between the shear bond strength to the tensile bond strength of an interface, to determine at which stress values sliding will occur.

Run	Mechanical properties					Thermal properties			
	Normal stiffness (GPa/m)	Shear stiffness (GPa/m)	Friction (°)	Dilation (°)	Cohesion (MPa)	Tension (MPa)	SBR ¹	Expansion rock (1/°C)	Expansion joint (1/°C)
100								8×10^{-6}	
101								8×10^{-5}	
102								5×10^{-5}	
103	210	210	35	30			50	8×10^{-6}	8×10^{-6}
104	210	21	35	30			50	8×10^{-6}	8×10^{-6}
105	210	210	35	30			50	8×10^{-6}	8×10^{-7}
106	210	210	35	30		0.5	100	5×10^{-5}	5×10^{-5}
107	210	21	35	30		0.5	100	5×10^{-5}	5×10^{-5}
108	210	210	35	30		1	100	8×10^{-6}	8×10^{-7}
109	210	21	35	30		1	100	8×10^{-6}	8×10^{-7}
110	210	210	35	30	1	7	100	3×10^{-5}	3×10^{-7}
111	210	210	35	30	1	7	100	3×10^{-5}	3×10^{-8}
112	210	210	35	30	1	7	100	5×10^{-5}	5×10^{-8}
113	210	210	35	30	1	7	100	7×10^{-5}	7×10^{-8}
114	210	210	35	30	1	7	100	1×10^{-4}	1×10^{-7}

Simulations were conducted for the period between January 2018 to April 2019, allowing for a three-month interval for model stabilization so that the initial comparison could encompass a timeframe of 13 months starting in April 2018. To better show the results, simulations have been plotted in two graphs in Figure 7-34. Figure 7-34a summarizes the simulations from Run 100 to Run 107 and Figure 7-34b introduces results from Run 107 to Run 114, including the calculated data for the East-West displacement of Slab 1. The calculated data are the complete time-series of fracture opening, with no missing data, created from the measured data set with missing points filled as previously discussed (Section 6.6.2). In the following subsections, the individual analysis of input variation and their effects on fracture opening are examined as a sensitivity analysis, focusing on the shape of the numerical time-series, peak values and differences to optimally match the calculated (measured) data.

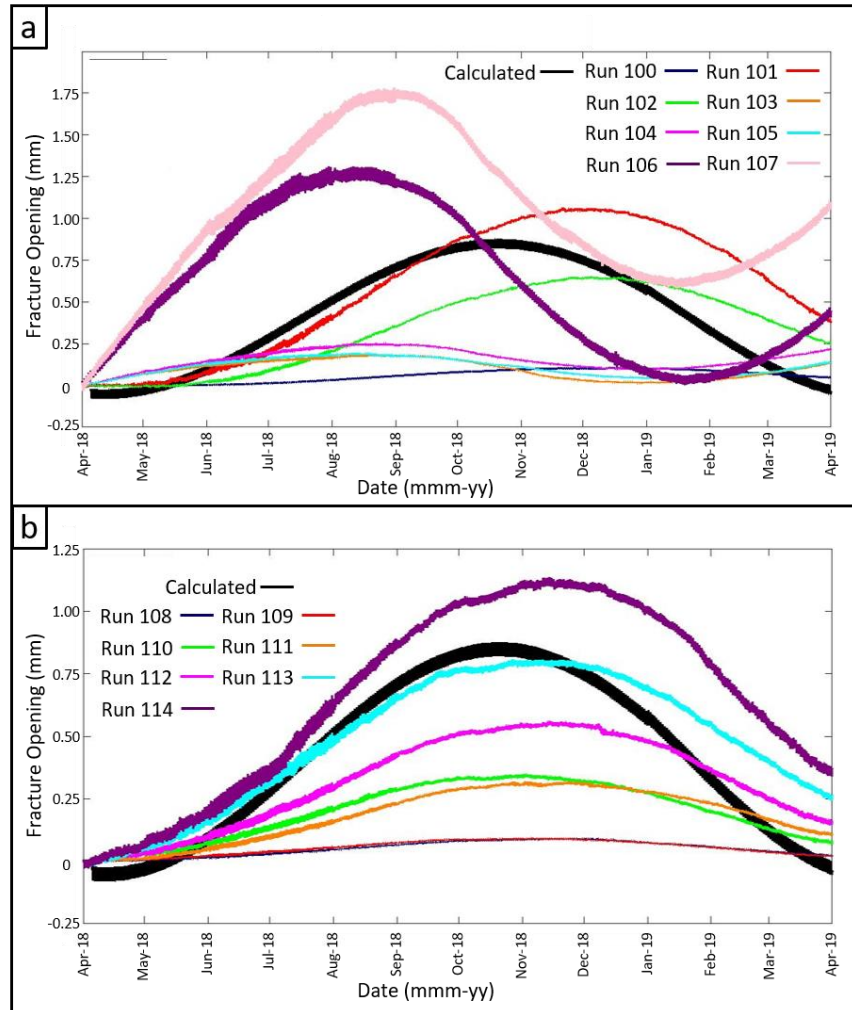


Figure 7-34: Summary of simulation results between April 2018 and April 2019 in comparison with the time-series of calculated (measured) data for a) Runs from 100 to 107 and b) Runs from 108 to 114. Inputs for individual runs are listed in Table 7-8.

7.5.1.1 Impact of thermal expansion coefficient

The thermal expansion coefficient is a key parameter that links thermal and mechanical cycles through the ratio of deformation of zones and the subsequent stress and strain rates. Hence, Run 100, Run 101 and Run 102 are set elastically with no joints, varying only the thermal expansion coefficient amongst them. Selected inputs (Table 7-8) of Run 100 were considered a base case, which had a coefficient ten times smaller than Run 101. Run 102 was set as an intermediate run between Run 100 and Run 101. Figure 7-35 introduces a comparative analysis, compiling time-series, correlation values and absolute differences.

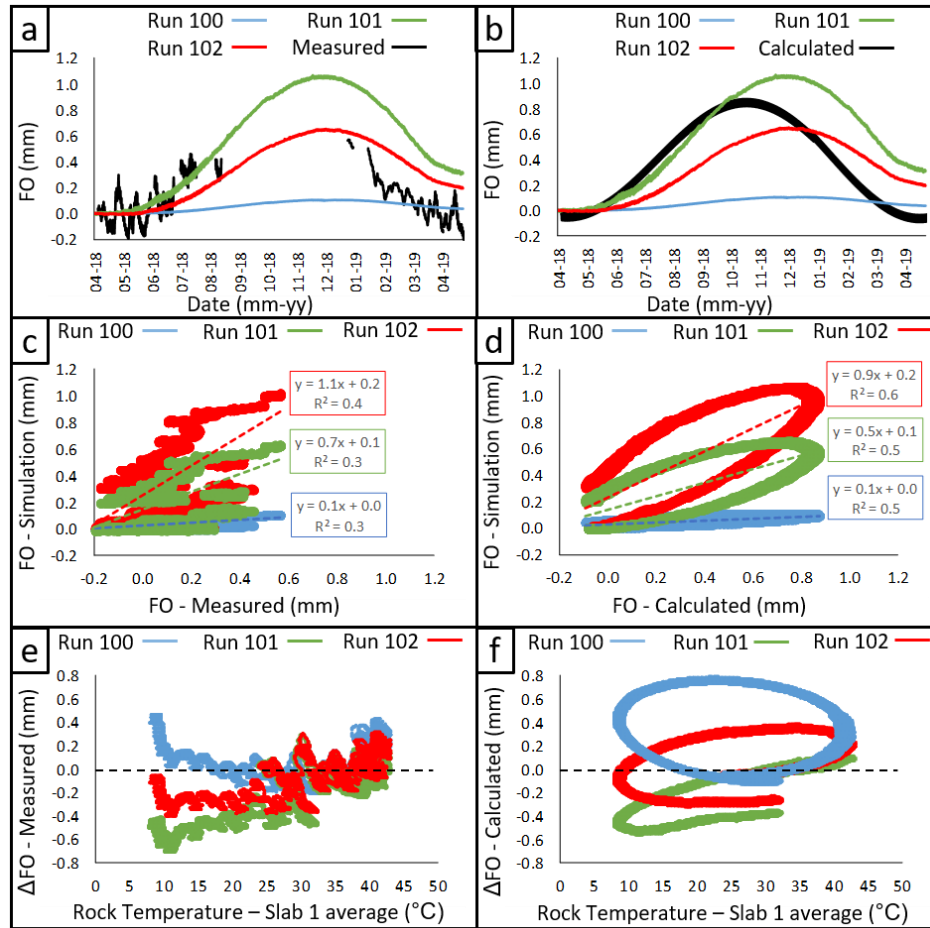


Figure 7-35: Comparative analysis of Run 100, Run 101 and Run 102, showing the impact of thermal expansion coefficient on thermo-mechanical simulation during the period between April 2018 and April 2019. Time-series compilation of a) simulation and measured data, and b) simulation and calculated data. Scatter plots between c) measured fracture opening or d) calculated data and simulation runs. Plots include the Pearson correlation factor between measured and simulated time-series. Likewise, scatter plots including d) calculated and simulation data. Fracture opening differences are defined as the measured minus the simulated values. Differences are calculated between simulations runs and e) measured and f) calculated data, plotted against the average rock temperature from modelling results for Slab 1.

The time-series plot in Figure 7-35a illustrates the increase in fracture opening with incremental variations of thermal expansion coefficient, resulting in increasing larger displacement values as the coefficient increases. For smaller fracture opening values between April and June 2018, the simulations closely follow the measured trend. However, the differences increase throughout the simulation period, particularly during the high-temperature summer months from July to October 2018. The simulation results converge again from November 2018 to April 2019, with differences within a range of 0.1 mm between runs.

When comparing the numerical time-series to the calculated data, as shown in Figure 7-35b, similar observations emerge, accompanied by a 60-day delay in peak values for the simulations. By filtering the simulated data according to the dates on which observations were reported, the

scatter plot in Figure 7-35c indicates that the Pearson correlation factor for measured data against numerical runs exceeds 0.3 for all runs, with Run 100 exhibiting the lowest correlation. However, there are more measured values during the colder months within this timeframe, thus missing the hotter months and peak values which reduces the overall fit. Run 101 has also a correlation value of 0.3, whereas Run 102 correlation is $R^2 = 0.4$. When comparing with calculated values, as depicted in Figure 7-35d, where Run 101 achieves a correlation value of 0.5. The highest correlation is achieved by Run 102, with $R^2 = 0.6$. The scatter plots display elliptical trends, representing the matching trends of the data before October 2018, and the subsequent displacement data. In October 2018, the peak value for fracture opening in the calculated data is reported, and simulation results exceed these peak values. Run 101 not only shows an absolute value higher than the peak, but it also reaches this peak in 60 days later, causing the trend to deviate from the overall calculated trend moving forward. Consequently, differences increased after October 2018, causing the plotted data to follow the second part of the ellipse for all simulations, with a clearer depicted for Run 101 and Run 102.

Relative differences in fracture opening between measured and simulated data are reported in terms of temperature variation in Figure 7-35e. Note that differences are reported as the measured value subtracted from the simulation. Temperature axis corresponds to the time-series of average temperature for the surveyed points located in the upper section of Slab 1 from the model. The largest differences are reported for the cooler temperatures associated with the final months of the simulation. Run 102 exhibits intermediate differences between Run 100 and Run 101, ranging from -0.2 to 0.2 mm. However, Run 100 mostly populates differences in the positive range due to its smaller displacements. Since Run 101 reports the largest displacements, the differences are also the largest. The comparison between calculated data and simulated is shown in Figure 7-35f. Run 100 shows differences of up to 0.8 mm for temperature ranges between 15°C and 30°C, and an average of 0.4 mm for extreme temperatures such as 10°C (the coldest) and 42°C (the hottest), indicating a range between 50% and 100% differences with calculated data accordingly. Conversely, Run 101 shows a maximum difference of 0.1 mm for temperature ranging from 25°C to 42°C, yet in the cooler range this difference can be up to -0.6 mm, which is 75% of the calculated fracture opening. Run 102 reports consistent differences ranging between -0.3 and 0.3 mm, around 38% of calculated data. As mentioned earlier, the major differences arise due to the shift in peak values, which increases the differences after October 2018.

7.5.1.2 Impact of joint presence and properties

Joints which divide the column into slabs were incorporated into the model as interfaces, with variations in their shear stiffness to analyze their impact on the displacement of Slab 1. This aimed to replicate the complex interaction between the joints and rest of the rock column, with the desire of capturing more realistic thermo-mechanical behaviour. Although Run 100 did not correlate well with on-site measurements; the same thermal expansion coefficient was applied to the jointed runs as an initial test to compare the influence of the joints and the effect on simulated outcomes by holding all other parameters the same. Figure 7-36 compiles the results, providing an overview of the simulations.

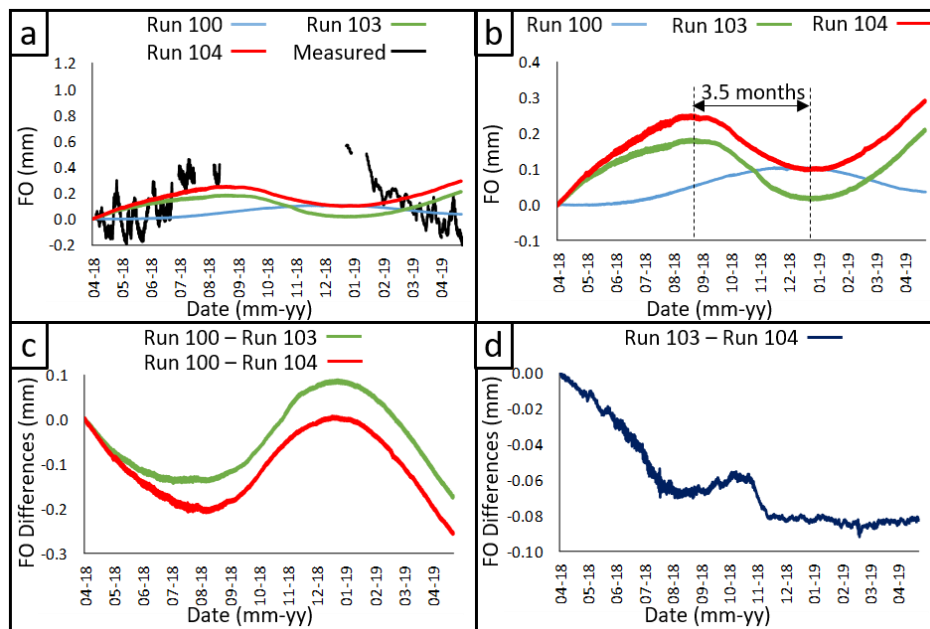


Figure 7-36: Comparative analysis of Run 100, Run 103 and Run 104, illustrating the impact of the presence of the joint elements and properties on the thermo-mechanical simulation during the period from April 2018 to April 2019. The time-series plots show the a) observed data and simulation results. Run 100 serves as the base case for comparison, so b) is a plot between time-series of simulated data only which indicates the shift in peak values between the base case and Run 103 or Run 104. Additionally, c) fracture opening differences (Δ) between the base case and Run 103 and Run 104 are plotted as time-series to illustrate the impact of the shear stiffness inputs. Similarly, the d) difference between Run 103 and Run 104 are plotted as time-series, as Run 103 minus Run 104 data.

The time-series plot against observed data are illustrated in Figure 7-36a, showing the alignment of all tests with the observed data trend during the initial and final months of the simulation. However, incremental differences between Run 103 and Run 104 emerge due to variations in joint stiffness. This is better illustrated in Figure 7-36b, which also displays a shift in peak values between Run 100 and Run 103 or Run 104. Run 100 exhibits a delay of 3.5 months in reaching peak values compared to Runs 103 and 104, underscoring the significant impact of the presence of joint elements and properties on the timing of mechanical response within the model. Both Run

103 and Run 104 achieve their peak values at the same point in time. The peak magnitudes are 0.19 mm for Run 103 and 0.25 mm for Run 104, indicating that Run 104 experiences greater displacement due to smaller shear stiffness. Figure 7-36c elaborates on the fracture opening differences between Run 100, serving as a base case, and Run 103 and 104. The differences are most pronounced from June to October 2018, where peak values occur. From November 2018 to February 2019, the differences between runs range from -0.1 mm to 0.1 mm, suggesting a temporary convergence in mechanical response. However, from March 2019 onwards, the differences increase again, indicating a divergence in the mechanical behaviour of the slabs over time.

The effect of shear stiffness differences is better depicted in Figure 7-36d, which compares Run 103 against Run 104. Since Run 104 was set with a shear stiffness ten times smaller than that of Run 103, the resulting displacements are larger, with a steady difference of -0.09 mm in the latter part of the simulation time. Under these settings, the difference caused by the stiffness property doubles the displacement achieved by Run 103. Nevertheless, the significance of interface properties lies in the increased displacement value, even at low thermal expansion coefficient settings. Additionally, the shift in peak values suggests a closer alignment with real measurements. It is worth noting that the strength settings of the interface are in the low range, with only frictional inputs, and no cohesion or tension included. This causes the joints to behave as loose discontinuities, resulting in larger displacements and failure in their nodes. The next section examines the influence of joint properties in more detail to determine how to control the movement on the interfaces in order to better match the measured time-series displacements.

7.5.1.3 Effects of thermal expansion coefficient contrast due to joint presence

A contrast in the thermal expansion coefficient between rock and joints was examined, using Run 100 as a baseline for unjointed rock mass. In the jointed simulation of Run 105, the coefficient was set an order of magnitude smaller than in Run 103. Both Run 103 and Run 105 share the same mechanical properties, lacking cohesion and tension. This setting represents a more realistic scenario where interfaces expand at a slower rate than the surrounding rock due to degradation from shearing, separation, and the potential influence of air temperature. It is important to note that other thermal properties were set as outlined in Table 7-6, so these variations do not affect rock temperature profiles. Figure 7-37 compiles the assessment of thermal expansion coefficient contrast.

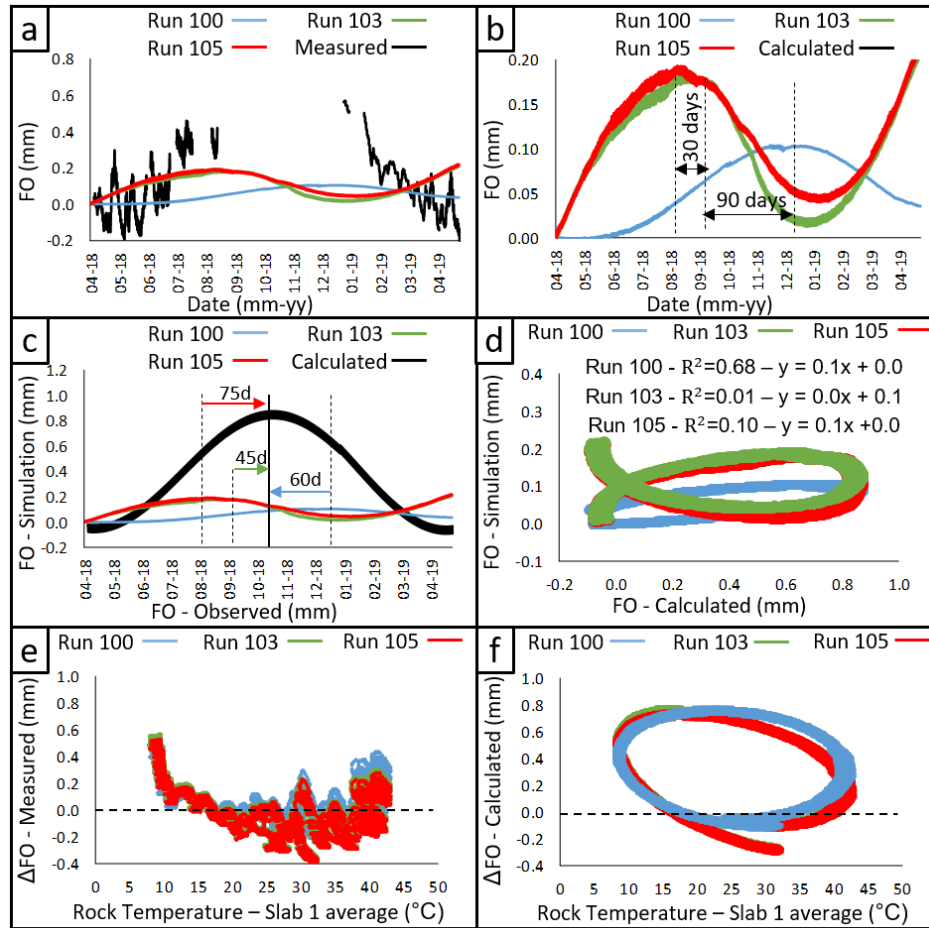


Figure 7-37: Comparative analysis of Run 100, Run 103 and Run 105, illustrating the impact of thermal expansion coefficient due to joint presence on thermo-mechanical simulation during the period from April 2018 to April 2019. Time-series compilation of a) simulation and measured data, and b) a plot between time-series of simulated data only to indicate the shift in peak values between simulation data. A time-series for c) calculated and simulated data highlighting the shift in peak values referred to calculated data, which is illustrated as d) a scatter plot reporting Pearson correlation factor. Fracture opening differences (Δ) between e) measured, f) calculated data and simulations, against average rock temperature for Slab 1 from modelling results.

The effect of joint presence is illustrated in Figure 7-37a, showing the shift in peak values between Run 100 and the other runs. Run 100 helps in determining how the addition of interfaces and the change in properties are impacting on the shape of the time-series simulation. The trend of simulations aligns for the first and last months of simulation when compared to measured or calculated data. When focusing solely on simulation results, as in Figure 7-37b, the fracture opening in Run 105 delays the peak value by 30 days compared to Run 103, and by 120 days compared to Run 100. Differences between Run 103 and Run 105 are 0.04 mm for the lowest range of values in the time-series, with a similar 30-day shift in peaks. This indicates that contrasts in the thermal expansion coefficient delay displacements. For instance, Figure 7-37c presents the calculated data time-series, highlighting the time that peak values occur. Run 100 shows a delay of 60 days, whereas Run 103 and Run 105 reach their peak values 45 and 75 days earlier than

the calculated data, respectively. This suggests that the coefficient contrast helps in temporal redistribution of the time-series, resulting in lower peak and trough values. As shown in Figure 7-37d, the Pearson correlation factor is 0.69 for Run 100, as previously discussed for the initial and last months; however, it is below 0.1 for Run 103 and Run 105, as the simulations do not closely match the calculated data in the initial and final months either.

Fracture opening differences between data from the measured and the simulations are depicted in Figure 7-37e, plotted against the average temperature in Slab 1 from simulation results. Run 103 and Run 105 exhibit similar trends, with the largest differences occurring at the coldest temperatures, ranging from 10°C to 18°C, between December 2018 and February 2019. Above 25°C, the differences fluctuate between -0.2 and 0.2 mm on average, which is not representative of the entire test due to the lack of observed data. However, the overall differences to calculated data, as illustrated in Figure 7-37f, show that all simulations result in a smaller displacement than the calculated one. Moreover, Run 103 and Run 105 achieve larger displacements at the beginning and end of the simulation due to the shape of the time-series. However, none of the simulations are close to the calculated peak value in magnitude or in the time that the peak value occurs. Specifically, Run 105 does not reach the same fracture opening differences at the end of a one-year cycle, relating to its lower deformation rate. As a result of the sensitivity in thermal expansion coefficient, it is evident that the contrast in coefficients is causing a temporal spreading of the time-series results, affecting the peak and trough displacement timing after joint interaction in the rock slab movement.

7.5.1.4 Impact of joint strength (tension)

The initial trials examined low strength interfaces with only frictional strength, which hypothetically would mean they are continuously fractured and susceptible to failure at specific nodes. This interface state has been previously examined in Section 7.3.2 concerning purely mechanical simulations, including scenarios with a tensile strength of 0.5 MPa. Consequently, the results presented in this section aim to evaluate the impact of stronger bonding on joint displacements. To this end, Run 102 was employed as the base case for an unjointed rock mass, whereas Run 106 and Run 107 represented jointed scenarios with a tension value of 0.5 MPa and an SBR (shear bond strength to tensile bond strength ratio) of 100. It is important to note that no thermal expansion coefficient contrast was applied. Variations in shear stiffness values were introduced between Run 106 and Run 107, with Run 106 having a shear stiffness ten times greater than that of Run 107.

The results are illustrated in Figure 7-38. The time series plot for observed and simulation data is depicted in Figure 7-38a, where the influence of joints, such as the shift in peak values and the increase in magnitude relative to the base case Run 102, is evident. Notably, Run 107 demonstrates a delay in peak values compared to Run 106, as better depicted in Figure 7-38b with only the calculated data. This delay amounts to 15 days from the Run 106 results, yet it aligns the peak value more closely with the calculated data's peak value. The peak value for Run 102 occurs 75 days after the calculated data peak, suggesting that both Run 106 and Run 107 experience a shift in peak values due to the presence of joints, as previously discussed. The inputs for Run 107 narrowed the gap between peak and trough values relative to the results of Run 106.

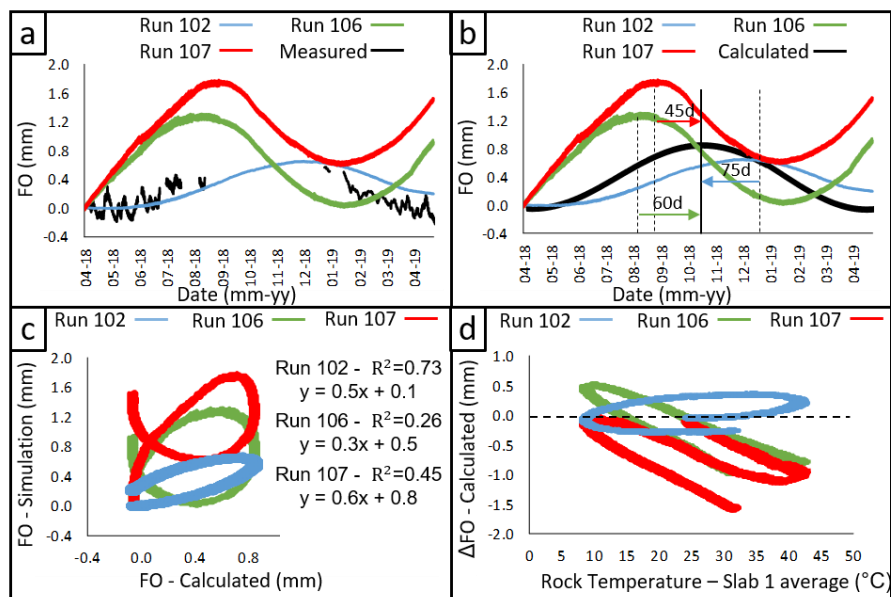


Figure 7-38: Comparative analysis of Run 102 against Run 106 and Run 107, illustrating the impact of the joint strength on thermo-mechanical simulations during the period from April 2018 to April 2019. The time-series plot illustrates simulation results against a) measured and b) calculated data. The latter highlights the shift in peak values between calculated data (base case) and all simulations, which is correlated in a c) scatter plot for simulated and calculated fracture opening, including the Pearson correlation factor. Differences (Δ) between base case and simulations are shown in a d) plot for fracture opening differences against average rock temperature for Slab 1 from simulation.

The cross-correlation between calculated and simulated data is presented in Figure 7-38c. Displacements from simulation results exceed the calculated data, with nearly double the extension for Run 106. This results in low Pearson correlation values for Run 106 and Run 107, with values of 0.26 and 0.45, respectively. Fracture opening differences illustrated in Figure 7-38d also indicate that the results for Run 107 surpass the calculated displacements, with the most significant differences occurring at the higher range of rock temperature. Due to the time-series shape, the results from Run 107 do not revert to the initial fracture opening values, implying a continuous opening expected due to shear of joints with a difference between April 2018 and April 2019 of 0.6 mm. Conversely, the results for Run 106 characterized by higher shear stiffness, allow

the model to approximate the original value, with a difference of 0.03 mm between April 2018 and April 2019, and exhibit similar differences across low and high temperature ranges throughout the simulation period.

Based on the above analysis, tensile strength becomes significant at low shear stiffness values, which allows larger displacements. Consequently, the tensile bond strength can be exceeded solely due to the effect of shearing. Although both scenarios commence with equal initial shear stresses on the interface planes, a temporal disparity is observed upon reaching peak values, augmenting the peak magnitude but resulting in a peak value shift of 15 days in the low shear stiffness scenario. A similar situation is observed for the troughs. Therefore, incorporating tension induced a contraction of the time series, shortening the wave length, when the shear stiffness value is below a certain threshold.

7.5.1.5 Combined impact of joint strength (tension) and thermal expansion coefficient

The combined effects of joint presence, thermal expansion coefficient contrast, and tensile strength of interfaces were systematically tested and compared. Run 105 served as the base case, characterized by the absence of tension on the joints, high stiffness values, and a specified thermal expansion coefficient contrast. Conversely, Run 106 and Run 107 were configured with a tensile strength of 1 MPa and shear stiffness values of 210 GPa/m and 21 GPa/m, respectively. The thermal expansion coefficient contrast was set at 8×10^{-6} for rocks and 8×10^{-7} for joints. Figure 7-39 compiles the results, presenting them in terms of time-series and highlighting differences between the calculated data and the simulation outcomes. As discussed in Section 7.5.1.3, the measured data exhibit a significant number of missing values in the higher temperature range, which complicates the comparison at peak values where adjustments due to input changes are most evident; hence, the use of calculated data is essential for comparison purposes in this assessment.

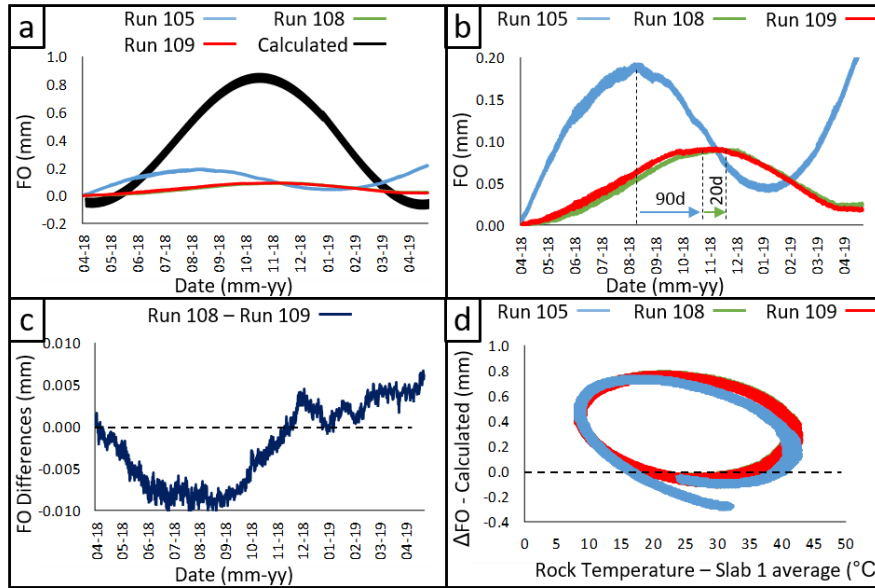


Figure 7-39: Comparative analysis of Run 105, Run 108 and Run 109, illustrating the impact of the joint strength and thermal expansion coefficient contrast on thermo-mechanical simulations during the period from April 2018 to April 2019. The time-series plot illustrates simulation results with a) calculated data. A zoom in of b) time-series of simulation results shows the shift in peak values. The c) fracture opening differences between Run 108 and Run 109; and the d) cyclic differences between calculated data and simulations against temperature of Slab 1 from simulation, illustrates the variation throughout the entire simulation period.

The sensitivity analysis in Figure 7-39a presents the time-series plot for simulation results and calculated data, highlighting smaller fracture opening values in the simulations, reaching only 25% of the calculated displacements. Shifts in peak values are observed not only between calculated and simulated data but also among the different simulation runs. Figure 7-39b zooms in on the simulation results, revealing a delay of 110 days in Run 105 compared to Run 108, attributed to the addition of tensile strength of the joints. Conversely, the peak value for Run 109 occurs 20 days earlier than for Run 108, due to a smaller shear stiffness. Run 105 exhibits the largest peak value, as the interfaces behave weaker, allowing greater displacement.

The fracture opening differences due to changes in shear stiffness are shown in Figure 7-39c, between Run 108 and Run 109, ranging from -0.01 mm to 0.005 mm, which represents 5% to 10% of the maximum displacement. The largest differences are observed during the hottest months, from June to September 2018, with smaller differences as both trends reach their peaks. From January to April 2019, Run 108 reports larger displacements than Run 109 because Run 109's low shear stiffness allows larger variations in displacement at smaller stresses. Figure 7-39d illustrates the differences over the full cycle compared to the calculated data. Run 108 and Run 109 show differences ranging from -0.05 mm to 0.75 mm. The largest differences occur at low temperatures (8°C to 15°C), while the smallest occur at high temperatures. Run 105 follows a

similar trend, widening at mid-range temperatures (20°C to 30°C) and failing to achieve initial results due to low strength and node failure, leading to greater displacement.

7.5.1.6 Combined impact of joint strength (tension and cohesion) and thermal expansion coefficient

The effect of cohesion on joint strength was investigated for two cases with different thermal expansion coefficients for joints: Run 110 with 3×10^{-7} and Run 111 with 3×10^{-8} . The thermal coefficient for the rock was the same for both runs, at 3×10^{-5} . The strength inputs for the joints were set equally, with a tension of 7 MPa and a cohesion of 1 MPa, as well as shear and normal stiffness settings both at 210 GPa/m. This ensured that any differences observed would result from the thermal expansion of the joints. Figure 7-40 presents the results comparatively, including on-site measurements.

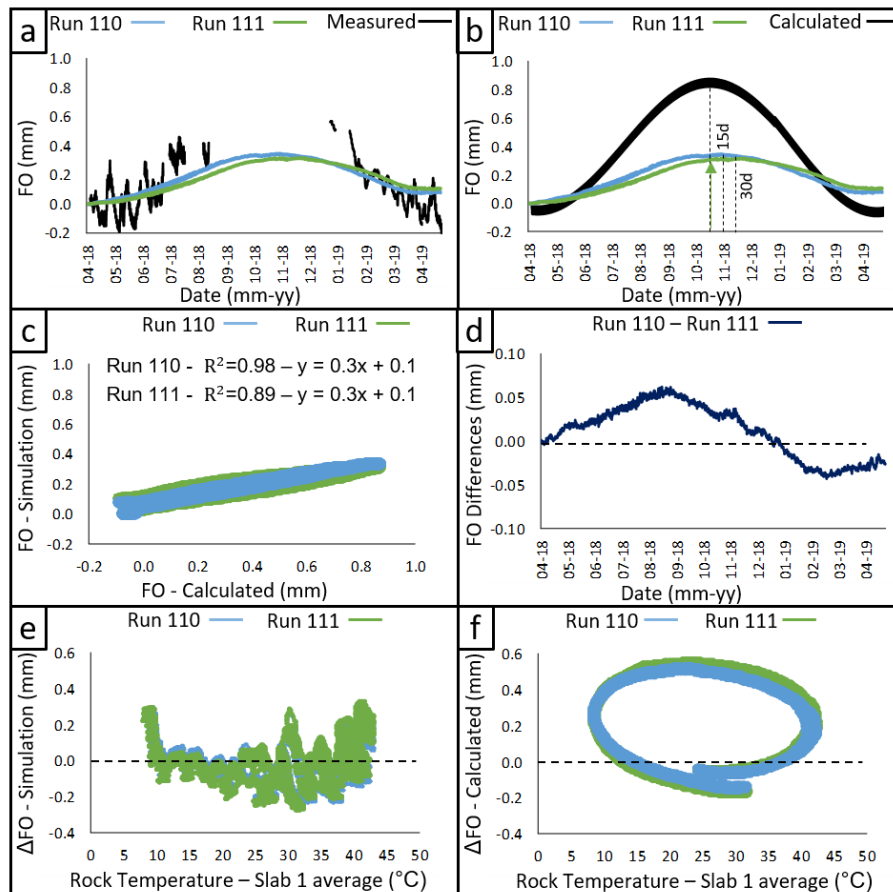


Figure 7-40: Comparative analysis of Run 110 and Run 111, illustrating the effect of interface cohesion and thermal expansion coefficient differences. Time-series compilation of simulated results against a) measured and b) calculated data. Scatter plots for fracture opening between simulations and c) calculated data, including the Pearson correlation factor. Fracture opening differences (Δ) between d) Run 110 and Run 111; and simulations and e) measured or f) calculated data against average rock temperature for Slab 1 from simulation results.

The variation in thermal expansion coefficients shifts the peaks of both time series, as shown in Figure 7-40a. Here, Run 110 reaches the highest displacement 15 days before Run 111. For small ranges of displacements, such as from April to July 2018 or January to April 2019, both runs show good agreement with the observed data. The peak values are better depicted using calculated data, as introduced in Figure 7-40b, where the peak magnitudes are half of those in the calculated data for both runs. However, the peak value for Run 110 occurs 15 days later than in the calculated data, whereas for Run 111, it is 30 days late. This implies that Run 110 better matches the calculated time-series temporally and in shape for the high peaks.

Scatter plots in Figure 7-40c show that the Pearson correlation factor for Run 110 is 0.98, which is higher than the 0.89 for Run 111. However, it is worth to note that these data sets do not perfectly match to calculated data since R^2 calculations do not consider the magnitude of the data, being invariant to scaling and shifting, but assessing how well the data points align with a linear plot. Differences between simulations are depicted in Figure 7-40d, for Run 110 minus Run 111, with higher values for Run 110 during the hotter months and being overpasses by Run 111 in the colder months. This reflects the shifting in peak values by reaching the troughs at different dates, then reflecting this difference at the end of the simulation time.

The FO differences between measured and simulation data are introduced in Figure 7-40e, against the average rock surface temperature from the simulations. Run 110 showed closer alignment with the calculated data. The average range for Run 110 is between 0.07 and -0.03 mm, fluctuating annually throughout the simulated period. These differences become more significant when compared to measured data. The measured data ranges between -0.3 and 0.3 mm, as shown in Figure 7-40e. More pronounced differences occur at high temperatures due to the low peak values reached by the simulations. As previously mentioned, the limited amount of measured data does not allow for a full cycle analysis. A comparison with calculated data in Figure 7-40f indicates that differences are greater for Run 111 across the entire range of temperatures than for Run 110. However, both simulations follow a similar pattern for the whole range of rock temperatures.

The combination of strength inputs along with the thermal expansion coefficient contrast reduces temporal differences between simulation and calculated time-series data, resulting in improved alignment. The addition of cohesion helps control fracture opening by limiting interface element failures, thereby minimizing differences in expansion coefficient variations between runs, even when there is an order of magnitude difference in joint thermal expansion between them.

7.5.1.7 Final adjustment of model parameters

Final adjustments of model parameters were made by varying the thermal expansion coefficient. Four runs were tested, with similar inputs for stiffness and strength of interfaces, following the analysis from Run 100 to Run 110. Figure 7-41 presents the results comparatively, including both observed and calculated data sets. The time-series plot in Figure 7-41a demonstrates the impact of the thermal expansion coefficient variation on resulting displacements. Higher coefficients result in larger displacements, aligning more closely with the observed data. All four runs align with the initial period from April to August 2018. However, disparities emerge during the hotter months, with Run 111 and Run 114 under- and overestimating the observed values, respectively. Run 112 closely follows the observed data trend, whereas Run 113 exceeds the observed data from December 2019 to April 2019. Comparison with calculated data (Figure 7-41b) reveals that Run 112 fails to reach the same peak values, exhibiting a flatter trend. Conversely, Run 113 matches the peak fracture opening, albeit with a 7-day delay relative to the calculated time-series.

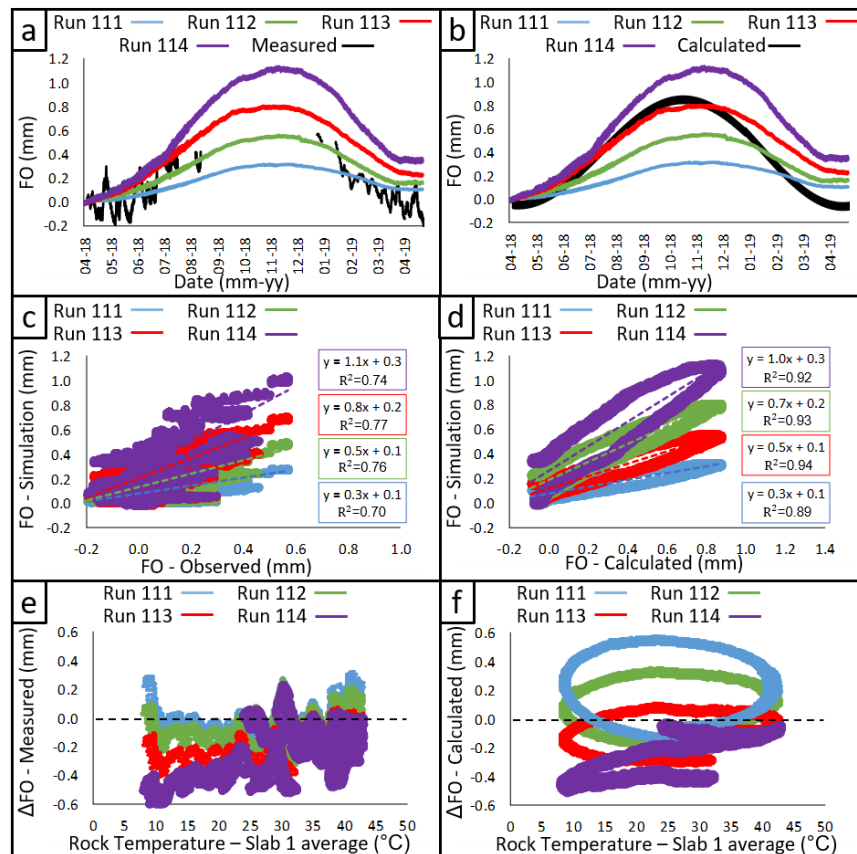


Figure 7-41: Comparative analysis of Run 111, Run 112, Run 113 and Run 114, illustrating the final calibration settings and variations in the thermal expansion coefficient for rock and joints on the thermo-mechanical simulations during the period from April 2018 to April 2019. Time-series compilation of simulations results with a) measured and b) calculated data. Scatter plots for fracture opening between simulations and c) measured or d) calculated data, including the Pearson correlation factor. Fracture opening differences (Δ) using as base case the e) measured or f) calculated data are plotted against rock average temperature for Slab 1 from simulation results.

The scatter plot in Figure 7-41c illustrates robust alignment between simulations and measured data, with Pearson correlation values exceeding 0.70 for all scenarios. The highest correlation, 0.77, is achieved by Run 113. When correlating the simulated with calculated data, higher Pearson values are observed, particularly due to the magnitude of peak and trough values (Figure 7-41d). The lowest correlation is observed in Run 111 (0.89), whilst Run 113 exhibits the highest (0.94). All simulations display an elliptical correlation with displacements deviating from the calculated ones, depicted by the sides of each elliptical trend.

The fracture opening differences between measured and simulated data against average rock temperature from simulation results is illustrated in Figure 7-41e. All simulations exhibit greater discrepancies at lower temperature (8°C to 20°C), consistent with winter months, where simulated fracture opening exceed observed values. Run 111 and Run 112 show the smallest differences across all temperature ranges, aligning best with the initial and final months. Figure 7-41f details differences with calculated data. Run 113 demonstrated the smallest discrepancies, ranging from -0.3 to 0.1 mm across the entire temperature range. In contrast, Run 111 exhibited the largest difference, ranging from -0.15 mm to 0.58 mm, followed by Run 114, ranging from 0 to -0.5 mm. Run 114 displays a distinct curve from the other simulations, consistent with the time-series in Figure 7-41b. Initially, differences are minor (-0.05 mm from April to July 2018), with an incremental value to -0.55 mm as temperature drops from 45°C to 8°C (August 2018 to January 2019), and remaining at -0.55 mm with an increase from 8°C to 33°C (February to April 2019). This pronounced trend in Run 114 is attributed to its higher thermal expansion coefficient.

The thermal expansion coefficient, in addition to the contrast between rock and joint, is crucial for this modelling. Adjusting this parameter aligns the model with the measured displacement values. Combined with interface orientation and properties, this adjustment produced Run 113, which best fits the observed and calculated data time-series.

7.5.2 Thermo-mechanical model implementation

The parameters identified in the model calibration stage provided the optimal inputs for simulating the fracture opening of the rock column. As part of the model implementation, the assessment of the joint stiffness was conducted to verify the model behaviour, varying only this input. New simulations were named as Run A and Run B, and properties are listed in Table 7-9. Thermo-mechanical inputs from Run 113 showed the most accurate correlation with measured and calculated data, hence all properties were inputted in the new runs but the shear stiffness of joints.

Table 7-9: Mechanical and thermal properties of interfaces for final thermo-mechanical simulations. Run A and Run B have interfaces explicitly set. ¹SBR: shear-bond ratio is an artificial value that defines the ratio between the shear bond strength to the tensile bond strength of an interface, to determine at which stress values sliding and failure will occur.

Run	Mechanical Properties						Thermal Properties		
	Normal Stiffness (GPa/m)	Shear Stiffness (GPa/m)	Friction (°)	Dilation (°)	Cohesion (MPa)	Tension (MPa)	SBR ¹	Expansion Rock (1/°C)	Expansion Joint (1/°C)
A	210	210	35	30	1	7	100	7×10^{-5}	7×10^{-8}
B	210	21	35	30	1	7	100	7×10^{-5}	7×10^{-8}

Comparing the last two runs in Figure 7-42 aimed to align peak values of observed and calculated data in terms of magnitude and temporal occurrence. Overall, Run B, with lower shear stiffness for joints, exhibited larger displacements compared to Run A. Initially, both trends closely aligned until their respective peak values, after which consistent differences emerged. Figure 7-42a illustrates simulation results and observed data, initially aligned but showing larger end-period displacements in simulations. Figure 7-42b highlights peak values, with Run B showing similar values, albeit occurring 5 days earlier than the calculated time-series compared to Run A.

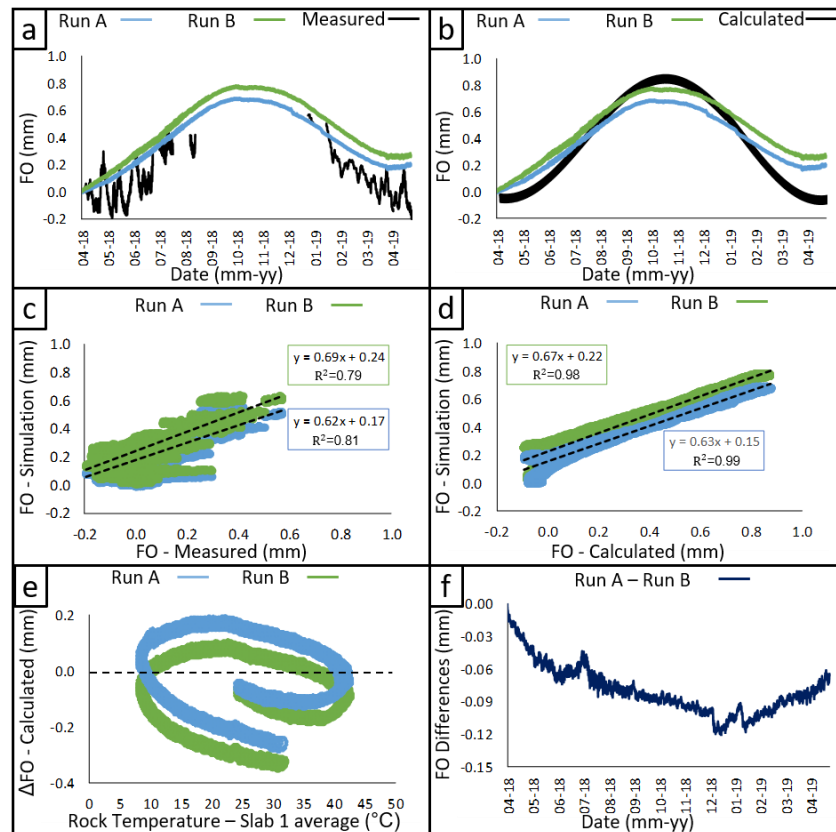


Figure 7-42: Comparative analysis between Run A and Run B for a simulation period between April 2018 and April 2019, including time-series comparison between simulations and a) measured and b) calculated data. Correlation plots with the Pearson correlation factor are shown in scatter plots against c) measured and d) calculated time-series, in addition to e) fracture opening differences between simulation and calculated data are included against rock surface temperature from simulations. Differences between f) Run A and Run B due to shear stiffness contrast are illustrated as time-series.

Scatter plots in Figure 7-42c for observed data indicate widespread distribution at lower displacement ranges due to missing data during hot months, delivering Pearson correlation coefficients of 0.81 and 0.79 for Runs A and B, respectively. Better alignment was achieved when compared to the calculated time-series, with correlation coefficients of 0.99 and 0.98 for Runs A and B, respectively. Significant differences were noted at smaller displacements, where simulations did not correlate well towards the colder months' end.

Fracture opening differences between calculated and simulated data, depicted in Figure 7-42d, show the largest disparities occurred at lower temperature ranges. Joint properties, such as thermal expansion coefficient contrast and stiffness, contribute to these differences, slowing down the back-cycling process. Differences in initial and final displacements were more pronounced for Run B. Assessing the effect of shear stiffness revealed a maximum difference of -0.12 mm between Run A and Run B, equating to an average difference of 15% against peak values ranging from 0.6 to 0.75 mm.

Despite this 15% discrepancy, the close correlation and shape of the time-series suggested both runs effectively simulated fracture opening from 2018 to 2019. However, Run B, with stiffer interfaces and a normal-to-shear stiffness ratio of 10, allows for greater shear displacements of the joints compared to a smaller ratio. This represents a more realistic scenario and also leads to larger strains, contributing to the failure of the rock column. Although a smaller ratio could generate more failed elements at the joint surface, there is no evidence that failure is occurring at the joint surface due to the thermal fluctuations. Instead, increasing displacements have been measured and are being used to calibrate the model. Furthermore, this ratio aligns with observations by Bandis, Lumsden, and Barton (1981), indicating that normal stiffness typically exceeds shear stiffness, with the difference varying based on normal stress levels. Mechanical results in Section 7.3.2 confirmed a principal stress range of 0.2 to 0.4 MPa for Slab 1, supporting the selection of a low shear stiffness for interfaces. Based on this analysis, Run B's simulation was selected to model column behaviour throughout the entire timeframe.

From the modelling behaviour, the reduction in shear stiffness resulted in larger shear displacements contributing towards the fracture opening values. Both simulations Run A and Run B showed similar time-series trends, and peak and troughs varied as expected for a change in this parameter. This reflects that if the model is perturbed at certain features, it will not deliver results beyond specific features. Hence, the model is capable to adjust the response in accordance to the nature of the perturbations or variations.

7.5.3 Summary of the thermo-mechanical simulation findings

The sensitivity analysis conducted provided valuable insights into the impacts of various inputs on the thermo-mechanical simulation for the current geometry, rock mass properties, and thermal boundaries. While separate mechanical and thermal analyses had been performed previously, the combined effects on the displacements of Slab 1, particularly the fracture opening values, were not well understood when standard parameters were used in a non-transient simulation. A summary of the main steps taken to match the time-series of calculated data is illustrated in Figure 7-43.

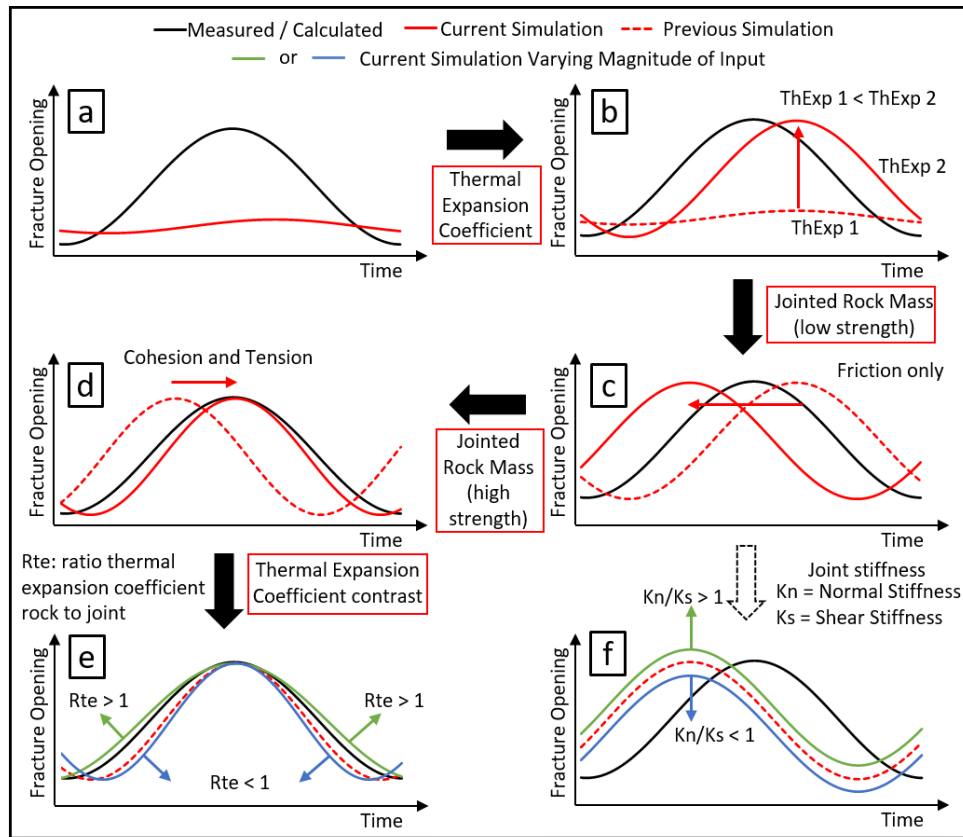


Figure 7-43: Schematic sequencing of sensitivity analysis compared to calculated data, from a) generic base case. The impact of b) thermal expansion coefficient variation, followed by c) incorporation of interface with low strength settings (only frictional). Interface settings for d) stronger joints and e) thermal expansion coefficient contrast between rock and joints contribute to displacement values. Another case for f) normal and shear stiffness of joints is depicted. Dashed line in every plot refers to the previous data set, whereas green or blue lines are the resulting trends at varying the magnitude of specific inputs.

The base case, depicted in Figure 7-43a, shows the results for low thermal expansion coefficients in an unjointed rock mass. The differences in fracture opening were observed not only in terms of magnitude but also in the temporal alignment of peak and trough values. Increasing the thermal expansion coefficient by at least one order of magnitude resulted in fracture opening values closer

to the calculated data, with a shift in peaks, although the magnitudes showed smaller differences compared to the base case, as schematically shown in Figure 7-43b.

Incorporating joints led to a shift in peak values, causing the largest fracture opening to occur months earlier than in the time-series of calculated data, as shown in Figure 7-43c. These joints were initially set with low strength, relying solely on frictional strength. Adding tension and cohesion inputs for the joint settings limited the delay in peak values, aligning both simulation and calculated trends closely, despite disparities in the initial and final months of the simulation, as introduced in Figure 7-43d. The contrast in thermal expansion coefficients between rock and joints became relevant in shifting the trough values, widening the sides of the time-series trends, as shown in Figure 7-43e. This effect can be measured using the thermal expansion coefficient ratio of rocks to joints (R_{te}). For R_{te} values smaller than 1, the time series becomes narrower, while for values greater than 1, the time-series distribution widens.

The effect of shear stiffness compared to normal stiffness properties was also of particular interest. Simulations showed that varying the ratio of normal to shear stiffness impacted fracture opening results in the order of 10-15%, with larger displacements for smaller shear stiffness. Figure 6-44f schematically illustrates scenarios where this ratio is greater than 1, meaning the normal stiffness exceeds the shear stiffness, resulting in larger fracture openings measured on the interface plane in a shearing manner. Conversely, a ratio smaller than 1 results in shorter displacements. However, such joint conditions, like very rough planes or compressible infills, have not been observed on-site.

The selected input parameters for Run B achieved a correlation of 0.98 between simulation results and calculated data for the initial year of measurements. Future endeavors will center on extending the simulation period to encompass the entire time-series of observed and calculated data, alongside detailed examination of the stress tensor at critical points such as the lateral fracture, Slab 1, and the interface plane. Subsequent analysis aims to elucidate the inelastic displacements experienced by the column above KV42 during the period spanning 2018 to 2023, particularly in light of the absence of significant extensions in long fractures or documented changes in the surrounding area. These investigations, coupled with considerations of temperature cycles, promise to advance our comprehension of the thermo-mechanical dynamics of the rock column, complementing the detailed analysis of interface presence and properties presented in this section.

7.6 Chapter Conclusions and Remarks

This chapter integrated unpublished monitoring data and findings from a numerical simulation in a 3D model for thermo-mechanical displacements of the rock column. The study employed FLAC3D®7.0 and a derived geometry from scanned sections to create a complex model, incorporating the key features for the simulations, such as the presence of older tectonic joints, a younger lateral tensile fracture, thermal boundaries and a notch section at the bottom of the column. The model underscores the relationship between geometry, mechanical properties and thermal inputs, amidst varying thermal gradients and geological features.

The modelling work was divided into four stages. The first stage involved mesh creation to better capture the location, extent, and orientation of specific features. Balancing refinement and the number of zones was crucial to optimize computational time and accuracy. Grouping zones was essential for later assigning distinctive properties and creating interfaces that act as joints. Mesh quality was assessed based on result stabilization with variations in zone numbers.

The second stage focused on mechanical analysis, providing insights into the rock mass's behaviour and its interaction with interfaces. The study began with an isotropic elastic constitutive model, analyzing the influences of boundary conditions on displacements and stresses, and transitioned to a more complex plasticity model using the Hoek-Brown approach. This progression allowed for a nuanced exploration of the rock mass's response to stress, revealing critical dependencies on joint configuration and properties.

A sensitivity analysis highlighted the indirect influence of various inputs on displacement magnitudes and stress distributions, emphasizing their role in structural integrity. Results indicated varying displacement trends influenced by joint settings, stress redistribution, and accumulation patterns from the presence of joints, highlighting zones susceptible to failure. Additionally, the assessment of rock mass strength and failure patterns elucidated zones prone to tension-induced damage. The observed spatial distribution of failed zones provided valuable data for model calibration and input parameter refinement.

The third stage, thermal analysis, aimed to simulate isotropic thermal conduction within a model region where temperature does not accumulate at the boundaries. This region constitutes 37% of the model's total volume, focusing on areas of interest to enhance computational efficiency while maintaining mechanical interaction capabilities during coupled simulations. Dynamic thermal boundaries were applied, i.e., input temperatures varied spatially and temporarily, adjusted to realistically represent seasonal variations. Temperature values at these boundaries were inputted

as sinusoidal functions with low, middle, and top regions that interchange during the simulation period. Infrared thermographic image analysis, discussed in CHAPTER 6 from Alcaïno-Olivares et al. (2023), assisted in defining these boundaries. A key aspect was the definition of thermal conductivity contrasts between rock and joints, identified as critical pathways for heat transfer. These contrasts influenced thermal conduction and subsequent heat dissipation, generating different temperature values at each slab and incorporating the thermal discontinuity and affecting continuity from the presence of joints. This was illustrated in temperature profiles and colour maps of time-series from linear surveys.

Thermal simulation results demonstrated robust validation against measured data, with Pearson correlation coefficients exceeding 0.9 across various surveyed points and linear surveys. Discrepancies, primarily observed during colder months, highlighted areas for further calibration to ensure accuracy under extreme temperatures. Transient simulations and different time settings in FLAC3D® were carefully managed to avoid extending temperatures and to better sequence simulation stages with dynamic conditions, mitigating the risks of artificial overheating and underestimating temperature distribution.

The final stage included thermo-mechanical simulations and input adjustments to match fracture opening displacements between simulated and measured data. Due to the complex geometry, dynamic thermal boundaries, and the role of interfaces, iterative calibration and sensitivity analysis were conducted to determine optimal inputs. The thermal expansion coefficient of rocks was a key parameter, generating significant displacements in the rock mass. All simulations were conducted under a mechanical isotropic elastic constitutive model to represent displacement variations due to reversible deformations in a period of 12 months.

Sensitivity analysis began with a non-jointed rock mass and progressed to incorporate interfaces and adjust properties such as the thermal expansion coefficient and joint strengths. This iterative approach aligned simulated fracture openings with measured data for Slab 1. The analysis highlighted the influence on the timing and magnitude of mechanical responses. Variations in the thermal expansion coefficient, coupled with mechanical inputs such as joint shear stiffness, tensile strength, and cohesion, significantly affected outcomes, demonstrating the importance of these parameters in capturing real-world behaviours. Efforts to match observed and calculated data sets achieved varying degrees of success. A schematic sequencing of input variations and their effects was established for application to this rock column. While some configurations closely matched observed trends, others showed discrepancies, especially during extreme temperatures.

Final results correlated with calculated data with a Pearson factor of 0.98, with the largest difference in fracture opening value of $\Delta 0.2$ mm during the first 12 months of comparison for RunB from the modelling implementation stage. A normal-to-shear stiffness ratio of 10 for joints was used to reflect realistic joint conditions. Plastic scenarios under Hoek-Brown constitutive model were excluded as they produced large displacements not observed on-site, related to failure of Slab 1 and lateral fracture which may have been exposed to cracking but not continuing failure or collapse of these features throughout to date.

Understanding the impact of key parameters and features within the rock column was crucial for achieving a close match between simulations and measurements. Fractures and rock mass properties, which had a substantial influence on the results in both two-dimensional and three-dimensional modeling, were calibrated accordingly. Notable instances are listed as follows:

1. The notch and slabs features, which are associated with different thermal boundaries due to temperature contrasts, resulted in varying deformation rates across the rock column. This differential movement significantly influenced the displacement of the slabs.
2. The thermal contrast between rock and joints, related to their thermal conductivity and expansion coefficients, influenced the temperature differences across joints and led to temperature accumulation in Slab 1, resulting in larger displacements. This contrast could be further investigated as a characteristic of the rock mass's thermal properties, with a specific coefficient accounting for the condition of the joints.
3. Joint properties were examined in terms of deformation and strength, with particular focus on cohesive strength and the normal-to-shear stiffness ratio. This ratio reflects the condition of the joint plane, with a larger ratio indicating that shear deformation is more likely than tensile failure, as compared to smaller ratios. Various values were tested, and a ratio of 10 was found to match measured data while aligning with joint conditions observed on-site.
4. The elastic parameters for the rock mass were determined based on the Geological Strength Index (GSI) assessment. The two-dimensional model had already reported an elastic isotropic mechanical behaviour for the rock mass, which was adopted in the three-dimensional analysis. The GSI assessment for the three-dimensional model also considered edges not included in the two-dimensional case, producing a GSI range of 50 to 70. Sensitivity analysis suggested a GSI of 60 for the thermo-mechanical simulations.
5. The strength of the rock mass played a critical role in visualizing failure near the lateral fracture and notch section, with particular focus on Slab 1. The exposed edge of Slab 1

helped validate the input parameters. While the rock mass is considered to behave elastically during the first thermal cycle (the first 12 months), assessing the strength parameters becomes more critical for long-term simulations. This level of calibration was not feasible in the two-dimensional model.

However, other settings were included in the simulations primarily to reflect the actual conditions of the rock mass, rather than being directly relevant to the results. These elements were not studied in the two-dimensional model but were incorporated into the three-dimensional version to better represent the geometry and potential impact the model's behaviour. These elements did not contribute to the calibration of the model, detailed as follows:

1. The debris layer, simulated using a Mohr-Coulomb plastic approach. While the pit walls and debris layer did not significantly contribute to the overall stability of the column, the debris confined the toe of the column and acted as a thermal barrier. However, this layer did not influence stability, and its omission could have improved computational efficiency.
2. The back cliff had no thermal influence on the rock column, even across the lateral fracture. The only potential deformation related to the surveyed point where fracture opening is measured, but other temperature patterns had no effect on the model's behaviour.
3. The bottom layer of the model assisted in dissipating stresses and temperatures, but further refinement of mesh elements in this layer was unnecessary for the model's objectives.
4. Friction and dilation had a lesser impact on the stability of the slabs compared to tension and cohesion. It is recommended that further efforts be directed towards understanding how these parameters vary over cycles, which is out of the scope of this research.

The overall interaction between all features, including the three joints, resulted in the successful calibration of the 12-month simulation. This validated the necessity of transitioning from a two-dimensional to a three-dimensional model, as key inputs and features were challenging to evaluate in cross-sections but could be addressed in a more complex three-dimensional geometry. For example, while fracture opening could be simulated in two-dimensional models, it was limited to fractures oriented parallel to the simulation plane, whereas the three-dimensional model could simulate opening and interaction of the full fracture network, including fractures oblique or perpendicular to the plane. Additionally, the three-dimensional model enabled the incorporation of temperature contrasts between the slabs and the notch, as well as the thermal boundary effects on the lateral fracture network. These interactions, which involve the complex interconnectivity of

fractures and their influence on stress distribution and temperature gradients, could not be fully captured in a two-dimensional approach.

Overall, the need for three-dimensional thermo-mechanical models is crucial, as they better capture thermal gradients and strain fluctuations across the geometry. For specific inputs like normal joint displacements or temperature contrasts, a two-dimensional model may provide valuable insights. However, incorporating thermal perturbations across the entire volume is necessary to grasp the full effect of inputs and features. The three-dimensional model demonstrated that dynamic thermal boundaries had to be modeled as changing surfaces, requiring seasonal simplifications, including the entire surrounding area of the rock column. Moreover, joint shearing during thermal cycles, observable only in three-dimensional cases, is crucial for future fracture growth simulations.

Future stages will focus on extending the model to analyze the inelastic displacements recorded on-site, spanning from April 2018 to July 2023. This includes stress generation from dynamic loading or mobilization linked to micro-scale failures or joint extensions. Continued refinement of these simulations will improve the understanding and prediction of the rock column's behavior.

CHAPTER 8 FRACTURE GROWTH IN THE ROCK COLUMN ABOVE KV42 RELATED TO THERMO-MECHANICAL DYNAMIC FATIGUE

The simulations presented in the previous chapter were instrumental in identifying the relevant inputs and their impacts on correlating fracture opening values with measured data. The elastic conditions with plastic joints were assessed to understand the behaviour of the rock column over the first year, whereas the necessary cyclic behaviour extends from April 2018 to July 2023. This chapter outlines the strategies for long-term simulations, focusing on potential fracture growth due to thermo-mechanical cycles. The analysis aims to guide further trials focusing on specific regions and contrasts in rock mass properties. The discussion connects the research outcomes to the geological and climatic conditions of the study site.

8.1 Measured Data: Elastic and Inelastic Displacements

The monitoring system at the rock column above tomb KV42 collects data on fracture opening values, environmental parameters, and rock temperature on the same plane where fracture opening is measured. The complete dataset is shown in Figure 7-2, which includes missing data that have been integrated using an average function. This new time-series, called "calculated," matches the measured data in peaks and troughs to define the displacement trend over the long term. As discussed in Section 6.6.2, despite the low thermo-mechanical cyclic behaviour within a period, the overall trend for fracture opening is positive over time, indicating the presence of inelastic displacements due to either the lateral fracture extension or deterioration of the notch section, or even both features combined. Figure 8-1 presents the observed and calculated data, including the analysis of elastic and inelastic fracture openings.

The analysis of elastic and inelastic fracture openings is introduced in Figure 8-1. The terms elastic and inelastic displacements refer to reversible and irreversible displacements as synonyms, respectively. Both terms are used interchangeably through the text. The time-series data are illustrated in Figure 8-1a for both measured and calculated values. An essential definition of "year period" differentiates between the calendar year (months within the same year) and the monitored year, which includes the twelve months from April to the following March. This distinction relates to the start of the monitoring network and the conditions at which a zero fracture opening was set, explaining the troughs in the time-series. The largest displacement is 1.33 mm for year period 5 (2022-2023), while the smallest displacement is -0.06 mm in year period 2 (2019-2020). The negative sign indicates a closing in the lateral fracture beyond its original value. Both time series are correlated in Figure 8-1b, with a Pearson correlation coefficient of 0.93. The alignment is better

towards the larger displacements, with a difference of 0.05 mm at the low range of fracture opening.

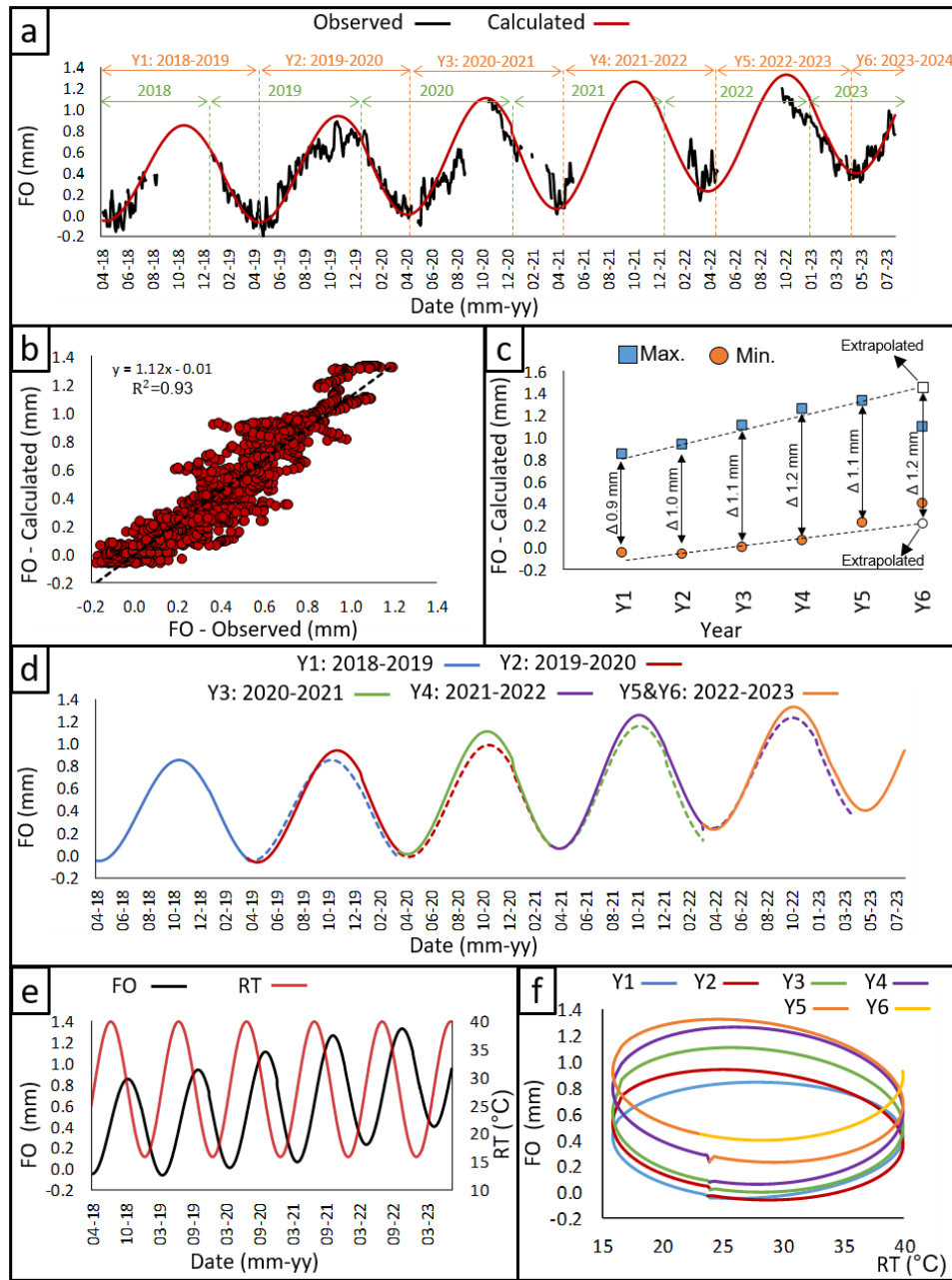


Figure 8-1: Monitored data of the fracture opening from the rock column above tomb KV42 span from April 2018 to July 2023. Data are plotted as follows: (a) measured and calculated time-series. Green arrows represent the calendar period along the series, while orange arrows denote the monitored year or year period from April to March, used for comparison. The "calculated" time-series fills in the gaps in the measured data, shown in (b) a correlation plot between both data sets. Fracture opening values for (c) maximum and minimum registers in each monitored year help in concluding the existence of inelastic displacements. The entire calculated series, showing (d) differences between previous and current monitored years, proves that displacements increase over time. Measured rock temperature (RT) and fracture opening (FO) are plotted as (e) time-series and (f) FO-RT cycles.

Maximum and minimum values of the calculated time-series were plotted by monitored year, along with the differences, in Figure 8-1c. Since peak values are typically reached in October or November; the peak for year period 6 has been linearly extrapolated, as well as for the trough. Both maximum and minimum increase over time, with an average difference of 1.1 mm, representing the maximum aperture reached by the lateral fracture in one monitored year. Fracture opening differences between monitored years are shown in Figure 8-1d, with values of 0.1 mm between year 1 and year 2, 0.17 mm between year 2 and year 3, 0.15 mm between year 3 and year 4, and 0.06 mm between year 4 and year 5. Differences are evident not only at peak values but also in matching the sides of the time-series curve. The variation between time-series represents the inelastic fracture opening, and the differences in peaks between years represent the inelastic displacement after discounting the elastic thermo-mechanical cycle. Since the low thermal expansion coefficient of sensors and the range of temperature fluctuation, there is no correction due to mechanical expansion of the displacement sensor, as discussed in Section 6.5.

These inelastic displacements are not a result of higher temperature trends within the measured period. As shown in Figure 8-1e, the daily average of fracture opening (FO) and rock temperature (RT) indicates that RT values have not changed considerably over time, despite the increasing FO trends. In fact, environmental parameters such as relative humidity, wind speed and direction, radiation fluctuate within similar ranges each year. Another observation is the shift in peak, with the RT peak occurring months earlier than the FO peak, indicating a delay in the thermo-mechanical cycle. This has already been discussed in Section 6.6.2 by Alcaïno-Olivares et al. (2023). The FO-RT plot in Figure 8-1f shows the annual cycle, with the largest FO values occurring at the low range of RT. Additionally, the largest differences between monitored years also occur at temperatures below 25°C, driving the inelastic displacements upward. For example, comparing year period 1 and year period 6, at the highest RT values, the fracture opening increased by $\Delta 0.5$ mm, whereas this value is $\Delta 0.9$ mm for the low range of temperatures. The values of inelastic displacement still match the rate of 0.2 mm/year concluded by Alcaïno-Olivares et al. (2023) for a shorter dataset of 3 monitored years.

The calculated data suggest the generation of inelastic strains, which may be stabilizing after noticeable fracturing occurs in the rock mass. However, no new fracturing was observable to the naked eye in the lateral fracture, which explains the ongoing increments in fracture opening. Evidence of deterioration in the notch section was reported from historical photographs, although no breakouts or spalling were observed during our fieldwork. This suggests an approach where

cracks are growing to redistribute stresses throughout the rock column, potentially inducing the larger fracture opening.

8.2 Modelling Strategies for Inelastic Displacements

Further modelling strategies aim to simulate fracture opening over the entire monitored period, following the insights detailed in CHAPTER 7, including plasticity settings that could also lead to inelastic displacements. Since the simulations provide principal (mechanical) and induced (thermo-mechanical) deformations, the inelastic response resulting from thermally induced stresses is addressed as part of the constitutive transient behaviour of the rock mass. Therefore, incorporating plasticity through thermo-mechanical fatigue concept is essential to understand the impact of stress tensor variation on the measured displacements and the subcritical condition of Slab 1.

However, it is crucial to note that previous results from a perfectly plastic constitutive model under the Hoek-Brown criteria showed that simulations for plasticity settings across the entire rock mass yielded fracture opening results of one order of magnitude larger than the measured values. In some instances, the displacements were oriented in the opposite direction. Hence, the integrated effect of the rock mass and localized failure did not clarify whether the new displacements were controlled by temperature. To inspect the trends under which simulations longer than one-year period could result in increasing trends, the modelling exercise simulated over 100 models, some of which did not fully represent the observed conditions, particularly those with plasticity set across the entire geometry. Therefore, the 50 most relevant simulations are reported in Figure 8-2, including the maximum values per month and per year for simulations and calculated data. Inputs are tabulated in APPENDIX H.

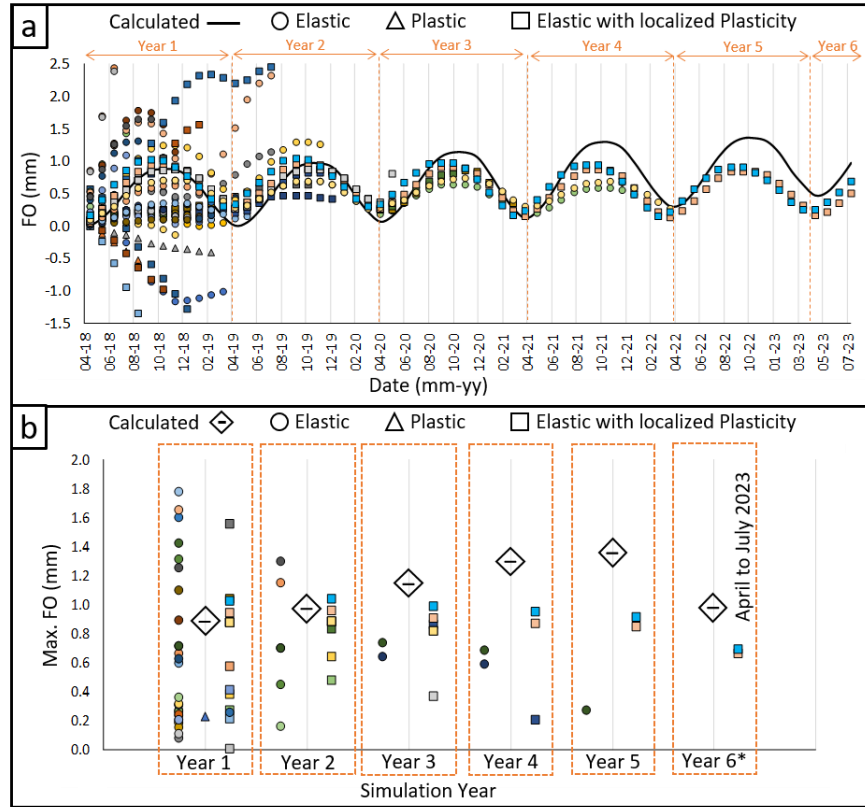


Figure 8-2: A summary of simulated fracture opening results for various instances of input variation is presented. Data are grouped by the constitutive behaviour of rock mass settings, including elastic, plastic, and elastic with localized plasticity. The maximum values are displayed for the calculated time-series and simulations on (a) a monthly basis and (b) a yearly basis.

The simulations are grouped according to the constitutive behaviour of the rock mass, such as elastic, plastic, and elastic with localized plasticity. The latter refers to instances where the overall geometry is set as elastic, but only specific regions of interest, such as the slabs, the notch, or the lateral fracture, are defined as plastic. Figure 8-2a presents the monthly maximum value per year period. The largest data are gathered in the first year, as initial simulations to calibrate the thermal and mechanical parameters for the elastic scenario were conducted in this period. Consequently, the models simulating FO for the second year period are more centered around the calculated maximum values after the initial calibration, with smaller deviations. Similarly, the third-year period includes simulations that align the peaks and troughs of the calculated data better than those simulated in the second-year period. However, the main differences are seen in the fourth-year period, in which the last two runs, Runs T-040 and T-050 from APPENDIX H, reported a decreasing long-term trend of FO.

This decreasing trend contrasts with the previously discussed inelastic displacements from measured data, not only in the magnitude of the peaks but also in the nature of the displacements.

Displacements are reported as increasingly larger towards the East, so FO values become larger throughout the monitored period. However, the longest simulations report an increase in displacement values towards the West which may be due to local deformations and stress accumulation in features such as the joints, the lateral fracture, and the adjacent cliff.

The opposite alignment is better illustrated in Figure 8-2b, with the maximum values per year. The simulations are grouped by mechanical constitutive behaviour around the maximum yearly value of the calculated data. It is important to mention that maximum and minimum values are not reached at the same date, so the plot only shows the alignment in terms of magnitude of the peak. First-year period results scatter around the maximum calculated data, yet an elastic and elastic with localized plasticity solution reached similar maximum values to the calculated data. In the second-year period, the simulated results tend to reach maximum values smaller than the calculated data, which were even of a smaller magnitude in the third-year period. By the fourth-year period, the trend shows that in the long term, the stresses are not being mobilized to the actual features to result in the measured FO.

To align the modelling results with the observations, four modelling strategies were tested to increase the fracture opening value throughout the simulation time, without using an overall explicit plasticity setting. The sequencing is illustrated in Figure 8-3. The thermal and mechanical properties of rock and joints, along with the thermal boundary definition, allowed the calibration of 12 months of simulation. This was achieved because elastic behaviour of the rock mass was expected to occur within one-year period, neglecting the measured hourly or daily fluctuations of fracture opening. After each cycle, or year period, a stress redistribution occurs, allowing for larger displacements hypothesized as an extension of the lateral fracture.

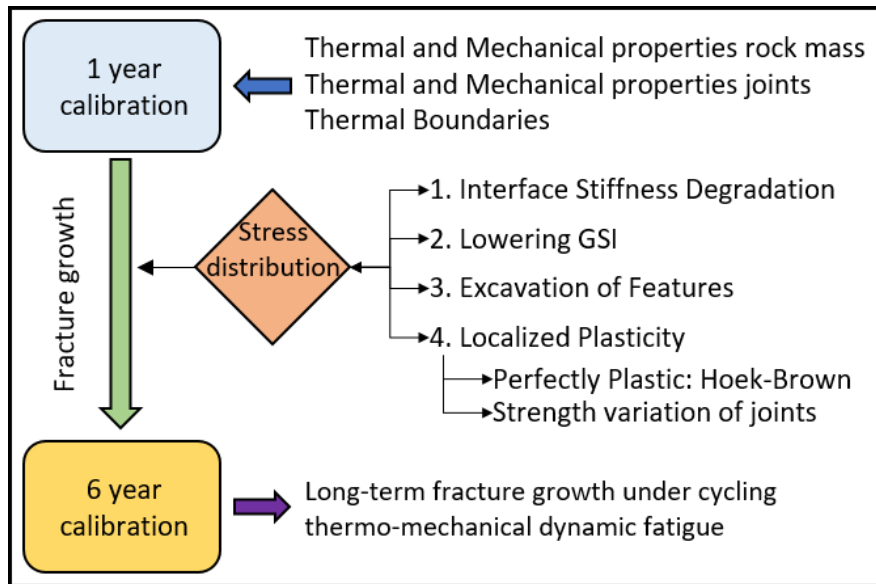


Figure 8-3: Sequencing of modelling strategies to achieve increasing fracture opening results.

The stress distribution may relate to one of these strategies, leading to the model calibration for the six years of measurements. Calibration is understood as aligning with the measured data by adjusting specific inputs. The sequencing of strategies was defined from the least computationally consuming to the most detailed implementation. The hypothesis is that the incremental strain after each cycle and the sustained increase in fracture opening help elucidate the actual conditions under which the lateral fracture extends under fatigue due to dynamic thermo-mechanical cycles. The inputs and results are detailed in the following subsections.

8.2.1 Interface Stiffness Degradation

The first trial aimed to enhance fracture opening by varying the normal and shear stiffness for Joint 1. The hypothesis was that reducing shear stiffness would result in greater movement of Slab 1, thereby increasing the fracture opening over time. This change was expected to redistribute stress within Slab 1, including the notch section and lateral fracture. While the notch and lateral fracture features are elastic, stress tensor fluctuations can provide analytical insights into the stability of these areas.

The base case is named Run 150, using properties outlined in Table 7-9 for Run B, with a normal to shear stiffness ratio fixed at 10. In Run 151, normal stiffness was set to 105 GPa/m and shear stiffness to 10.5 GPa/m. All other properties remained as in Run 150. Results for Run 151, simulated only until October 2020, are compared with the fracture opening calculated time-series in Figure 8-4. Figure 8-4a displays the daily average fracture opening values. Run 150, as the base case, showed cyclic compliance with adjustments described in CHAPTER 7. However, the

overall trend over the three-year simulation period decreased, with current maximum values lower than previous years. Run 151, with reduced stiffness, yielded similar fracture opening results to Run 150.

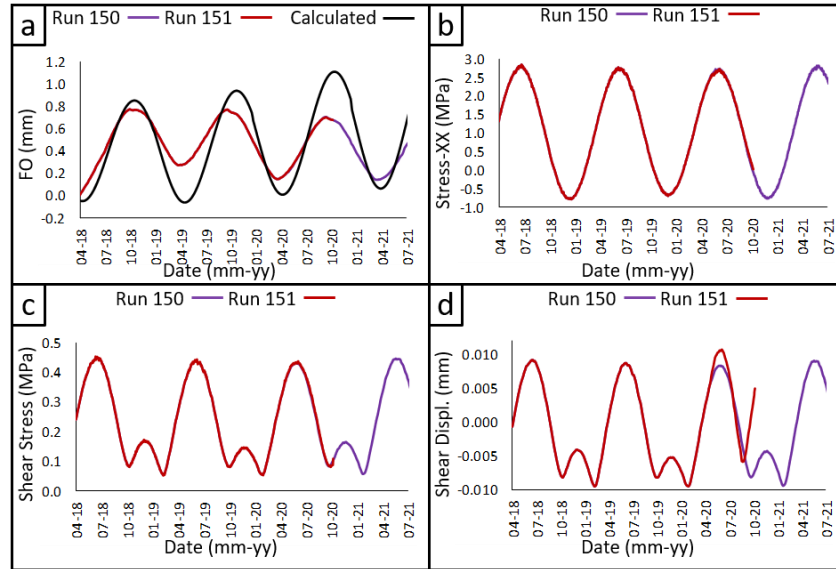


Figure 8-4: Daily average results from long-term simulations with varying stiffness of Joint 1 are presented. (a) A time-series comparison between the calculated data and simulation results from Run 150 and Run 151 is shown. (b) Horizontal stress along the x-axis is plotted for both simulation datasets. (c) A comparison of shear stress in Joint 1 over a three-year period is provided. (d) Shear displacements are plotted for both runs.

Stress analysis between simulations is shown in Figure 8-4b for horizontal stress along the x-axis, parallel to the joint plane. Stress fluctuated between 2.8 MPa in hotter months and -0.8 MPa in colder periods, with average differences of $\Delta 5$ kPa, slightly higher for Run 151. Shear stress values on the Joint 1 plane, for the upper region of Slab 1, are presented in Figure 8-4c. These values fluctuated between 0.45 MPa and 0.05 MPa, with average differences of less than $\Delta 1$ kPa, indicating higher shear stresses for Run 151. Both horizontal and shear stress trends follow similar patterns with comparable peak and trough values.

Major differences are observed in shear displacement of Joint 1 after the second-year period of simulation, as shown in Figure 8-4d. The peak difference in the third year corresponds to node element failure at the joint plane, localized at the western part of the column. This failure, related to reduced normal stiffness, was not seen in the base case. Despite this, shear stress values under the current regime are below 0.1 mm, having minimal impact on fracture opening values.

In previous simulations, shear displacement contributed up to 10% of the fracture opening result. The reduction in shear stiffness increased this contribution by less than 1%, with a peak difference of $\Delta 0.0025$ mm for Run 151. This suggests that a 50% reduction in shear stiffness at a normal to

shear stiffness ratio of 10 results in a fracture opening contribution of less than 1%. Differences between calculated data and simulations increased over time, reaching 20% in the first year and 35% and 45% in the second and third years, respectively. To significantly affect fracture opening trends, stiffness values would need to be reduced by at least two orders of magnitude, which appears geotechnically unrealistic, unless the ratio between stiffness had to be reduced as well. Additionally, stress redistribution due to displacements and node failure might bring peak values closer to calculated results, but this would require more brittle joint properties than observed during the past five years of fieldwork.

8.2.2 Lowering the Assigned Geological Strength Index (GSI)

The impact of crack growth and progressive fracturing was examined by varying the Geological Strength Index (GSI) in Slab 1, particularly in the upper and notch regions. The GSI, which reflects the amount of discontinuities and surface conditions as an assessment of the rock mass competency, was reduced to numerically represent the decreased competency of the rock mass due to crack generation or even the extension of fractures. Thus, the GSI values were progressively lowered to adjust the rock mass stiffness in elastic simulations.

Run 152 was conducted with an elastic solution to prevent large displacements in Slab 1 due to localized failure and joint orientation. The initial GSI of 60, consistent with Run 150, was adjusted over time, first to 55 in March 2019, then to 50 by the end of 2019, and finally to 45. The results of these simulations were compared with the calculated data, as shown in Figure 8-5. Figure 8-5a presents the time-series of fracture opening (FO) for different GSI values. None of the simulations demonstrated an increasing trend in FO, with discrepancies between calculated and simulated data growing over time. Specifically, Run 152 exhibited smaller displacements for both peaks and troughs compared to Run 150. Figure 8-5b illustrates the average horizontal stress in the East-West orientation, showing a decreasing trend for Run 152. At a GSI of 45, the peak stress was 2 MPa, compared to 2.8 MPa in Run 150. The reduction in GSI resulted in stress being redirected towards Slab 2, which exhibited an increasing trend in horizontal stress.

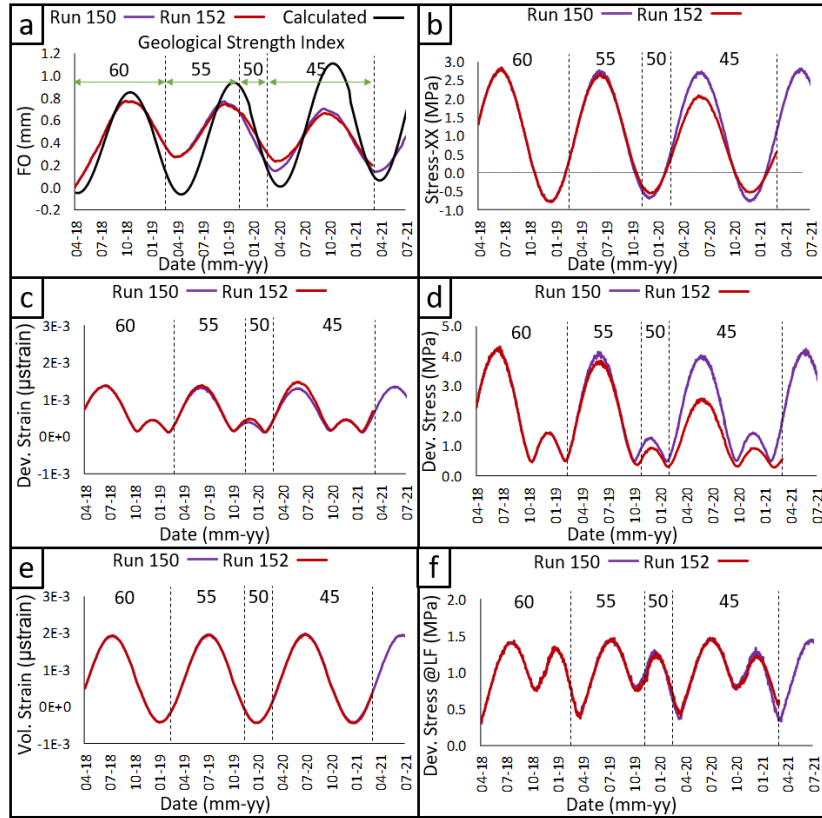


Figure 8-5: Daily average results for simulations Run 150 and Run 152, including changes in GSI over different intervals. The a) fracture opening values are compared as time-series, associated with b) stress in the horizontal East-West orientation on the x-axis. The c) deviatoric strain, d) deviatoric stress, and e) volumetric strain from simulations are displayed as time-series averages for the upper part of Slab 1. Exploratory data for f) deviatoric stress at the lateral fracture tip in the northern edge are also plotted as time-series for both simulations.

The deviatoric strain increased over time in Run 152, as depicted in Figure 8-5c, with peak values exceeding those in Run 150. However, the deviatoric stress decreased over time, as shown in Figure 8-5d, with the maximum difference between runs being $\Delta 1.8$ MPa, and higher values observed in Run 150 for a GSI of 45 in Run 152. The volumetric strain fluctuated with similar peak and trough values in both runs, as shown in Figure 8-5e, regardless of the GSI. Stress distribution associated with elastic deformation of Slab 1 and volume change under shearing was not well represented in these elastic scenarios. Stress fluctuations of σ_1 and σ_3 diminished over time in Slab 1, while they increased in Slab 2. The lateral fracture exhibited inconsistent stress behaviour, as illustrated in Figure 8-5f, influenced by the stresses in Slab 1. Deviatoric stress in Run 152 was higher during hotter months and lower during colder periods compared to Run 150.

The incorporation of dilation in future models could improve the representation of rock mass deformation and local stress accumulation due to positive volume changes associated with crack growth as seen for the deviatoric strain of Slab 1. This aspect was not implemented in Run 152, and it may be relevant for accurately modelling the fracture opening by allowing the volumetric

change which was not observed to happen when comparing both simulations. Although dilation is related to failure of material, the parameter needs to be inputted under plastic conditions which is not directly captured for the Slab 1. Hence, an analysis of sensitive regions in the model is done prior to study dilation impacts on the displacements.

8.2.3 Excavation of Sensitive Features

Stress distribution leading to increasing trends for fracture opening (FO) was also tested by modelling the excavation of relevant features affecting the stability of the rock mass. The excavations were modelled after the second year of simulation. These features included the notch section at Slab 1 and the lateral fracture, as illustrated in Figure 8-6a and Figure 8-6b, respectively. The notch section was excavated by 30 cm from its eastern edge, providing more clearance to the free bottom edge of Slab 1, in simulation Run 153. The lateral fracture was excavated vertically by 30 cm along the entire feature, with results reported in Run 154. Both excavations were carried out at the beginning of the third-year period (April 2020 – March 2021) based on the base case Run 150. All simulations were set to elastic, with plasticity settings applied only to the joint planes. The start of the excavation is indicated by an arrow in each plot of Figure 8-6. Results are reported as the average value of the upper part of Slab 1 or local data from surveys at N1 or LF (Figure 8-6a,b).

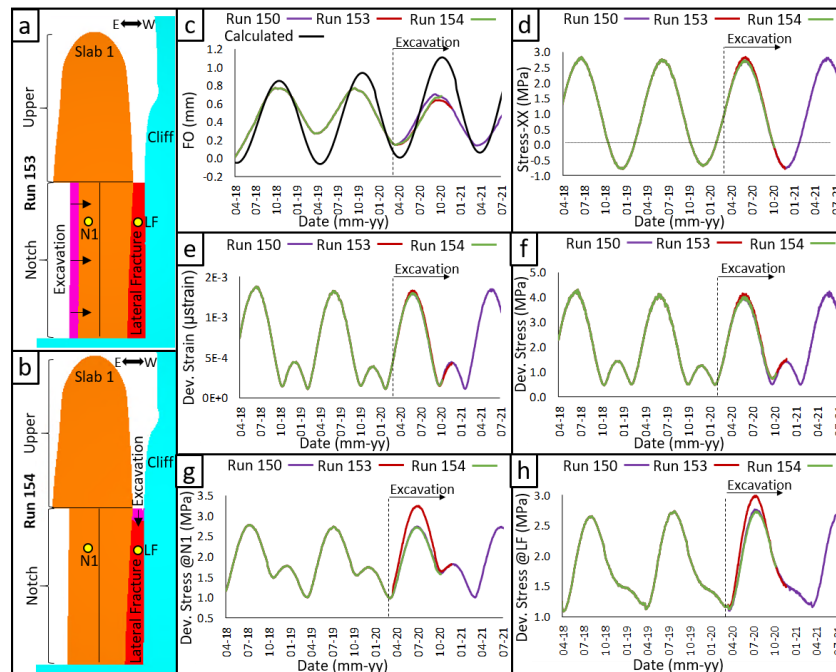


Figure 8-6: Daily average results for Run 153 and Run 154, simulating the excavation impacts on a) the notch and b) the lateral fracture, respectively. Run 150 is the base case for unaltered geometry. The illustrations indicate the date when features were excavated. c) Fracture Opening (FO) results are compared between simulations and calculated data, as well as d) horizontal stress oriented along the x-axis. Deformation is reported as e) a time-series of deviatoric

strain of Slab 1 average, whereas the stress tensor is reported as deviatoric stress at three locations, such as f) Slab 1 average, g) N1, and h) LF.

The FO time-series showed that all runs had a decreasing trend, similar to the base case after the excavation, as illustrated in Figure 8-6c. The peak values of the excavated instances were shorter than those of the base case. However, Run 154 delivered slightly larger displacements than Run 153, with a difference of $\Delta 0.03$ mm, associated with the reduction in the rock bridge between the rock column and the adjacent cliff. When analyzing the East-West oriented stress, Run 153 had a larger peak stress value in compression than Run 154. The stress fluctuated similarly to Run 150 at the troughs in the tensile state, as shown in Figure 8-6d.

The average deviatoric strain for the upper section of Slab 1 is depicted in Figure 8-6e, showing larger deformations for Run 153 compared to Run 154. The results for Run 153 aligned with Run 150 strains during the hotter months but became smaller during the colder months. However, the deviatoric stress time-series in Figure 8-6f indicate that stresses were greater for Run 153 than Run 150 throughout the entire simulation period after the excavation was set, even during colder months. Run 154 exhibited smaller deviatoric stress than Run 153 but reached greater deviatoric stresses than Run 150 during the colder months. This variation is attributed to the stress distribution resulting from the excavations.

Deviatoric stress distribution is characterized at two points: N1 in the notch section and LF below the excavated region in the lateral fracture. At N1, the peak stress increases by $\Delta 0.4$ MPa when the notch is excavated, as illustrated in Figure 8-6g. However, when the lateral fracture is excavated, no stress is mobilized towards the notch section, as the time-series of Run 154 aligns with the base case. When tracking the stress at LF, as shown in Figure 8-6h, the excavation of the notch mobilizes stresses towards this location, increasing the peak deviatoric stress by $\Delta 0.2$ MPa. The deviatoric stress at LF does not change considerably, yet it lowers the peak by $\Delta -0.01$ MPa, which may be related to relaxation due to the removal of the load.

Despite Run 153 delivering smaller peak FO values than other simulations, the excavation of the notch section had a more significant impact on the deformation of the rock mass by distributing stresses to the upper slab, the notch, and the lateral fracture. Larger FO results could potentially be achieved if failure of these zones occurs, associated with plastic strains and dilation. On the other hand, the excavation of the lateral fracture resulted in larger FO by shortening the rock bridge with the adjacent cliff but did not significantly influence the relevant features' stress. This suggests that a more focused analysis on the notch, rather than the lateral fracture, could enhance the simulation of rock column displacements.

8.2.4 Localized Plasticity: Notch Section of Slab 1

Plasticity was incorporated in the model at the notch section of Slab 1 specifically, not only to test the impact on fracture opening but also to emulate the current condition of the toe of Slab 1 as reported in CHAPTER 7 during the model construction. In addition, previous results for the induced excavation showed that the notch had a higher influence on the stress distribution results than the lateral fracture itself. Two scenarios were simulated: one with the eastern half of the notch section set as plastic, called Run 155, and a second one with the whole notch as plastic, called Run 156. The Hoek-Brown parameters were set with a dilation angle of 25° for both modelling instances, following Walton and Diederichs (2015) guidance. Strength values were input for a strong rock mass condition, with a GSI of 70, UCS of 55 MPa, and tensile strength of 8 MPa. Figure 8-7 illustrates the thermo-mechanical results for both instances, compared to calculated data and the base case simulation, Run 150.

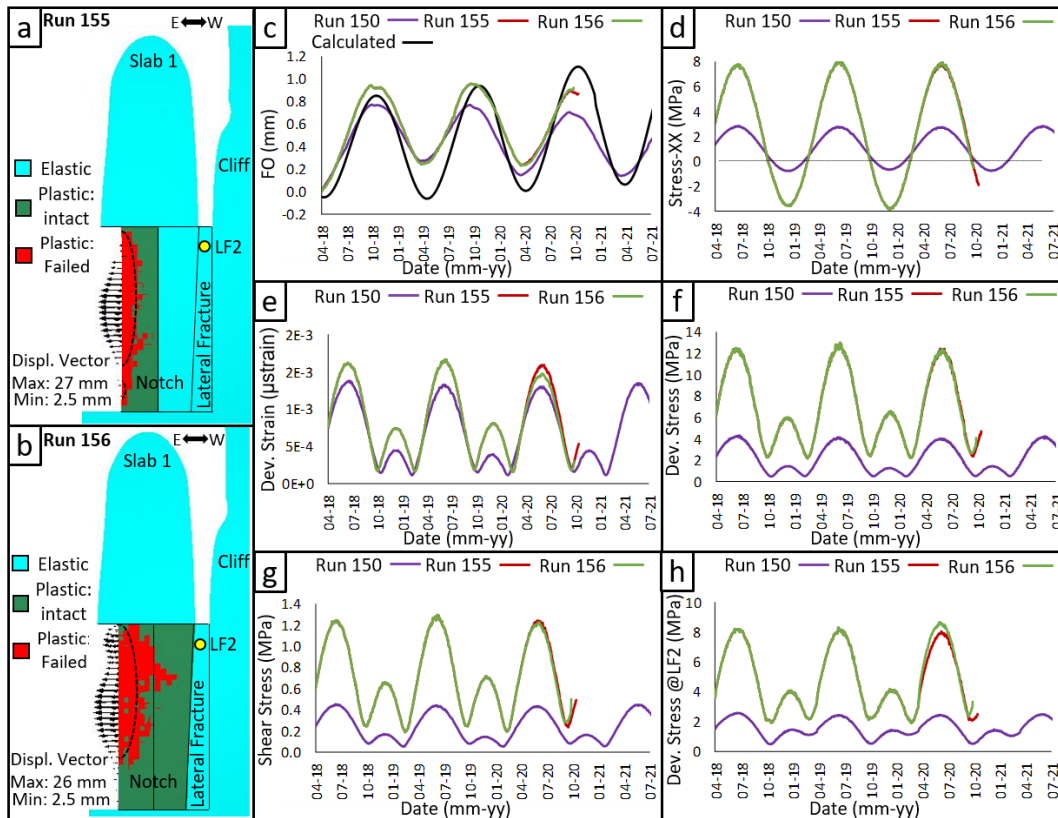


Figure 8-7: Daily average results for Run 155 and Run 156, simulating the localized plasticity at the notch section of Slab 1 for the a) eastern half and the b) entire notch, respectively. A legend indicates the behaviour of zones such as elastic, plastic intact (non-failed), and plastic failed zones. Run 150 is the base case for the elastic solution, with no excavation or GSI variation. c) Fracture Opening (FO) results are compared between simulations and calculated data, and d) horizontal stress oriented along the x-axis is plotted for simulations. Deviatoric e) strain and f) stresses are plotted as time-series as the average result on Slab 1 for each simulation. Also, g) the average shear stress in Joint 1 for each simulation is plotted as a time-series. Stress distribution towards the h) lateral fracture as a deviatoric stress time-series is recorded at LF2.

The mechanical settings for Run 155 are displayed in Figure 8-7a, showing the state of the zones at the end of the simulation. Zones outside the plastic region behaved elastically due to the settings. However, the plastic region showed intact and failed zones due to shearing and tension. The failed region did not reach the western half of the notch section, yet it extended vertically from the upper part of Slab 1 to the bottom for the outer 25 cm of the region. The displacement vectors displayed larger movement of the failed zones at the central and upper parts of the notch, with a maximum value of 27 mm.

Comparatively, the state of the zones for Run 156 showed deeper failure within the notch, as depicted in Figure 8-7b, extending horizontally to 32 cm. This scenario had a shorter vertical extension than Run 155, inducing larger displacements at the boundary with Slab 1 than those reported for Run 155. Nevertheless, the maximum displacement vector reports 26 mm at the central part, which is close to the reported value for Run 155. The horizontal extension shows that in the upper half of the notch section, the failure reached the western half, leaving the other zones intact.

The impact of the localized failure on fracture opening (FO) is shown in Figure 8-7c, where both Run 155 and Run 156 have larger FO results than the base case. During the first year, the model starts with failed zones that raise the FO results by $\Delta 0.1$ mm compared to the calculated data, and by $\Delta 0.15$ mm compared to the base case model. However, the current modelling instances aligned better with the calculated data in their peak values after the first-year period, still showing a decreasing trend, which is less steep than that reported for Run 150. For the troughs, at the end of the second-year period, both simulations reached lower FO values than in the first-year period.

Horizontal stress values in the East-West direction are averaged for the upper part of Slab 1 and presented in Figure 8-7d as time series, compared to the base case. The stresses for the plastic case are almost three times higher for the localized plastic solution, with more mobilization to Slab 1, for both peaks and troughs. The peak value for the third-year period showed that Run 155 mobilized larger stresses than Run 156, with a difference of $\Delta 0.08$ MPa, potentially associated with failure occurring during the peak temperatures in a smaller region. This variation is more pronounced when analyzing the average deviatoric strain in Slab 1, as shown in Figure 8-7e. Overall, plastic simulations delivered larger deviatoric strains than the base case, with trends. However, the difference is observed in the third-year period with Run 155 delivering larger deformations for the peak values.

Analysis of specific features indicates that the mobilization of stresses acts differently for Run 155 and Run 156, and that plastic scenarios induce larger stresses than the elastic solution. For instance, Figure 8-7f displays the average deviatoric stress time series of Slab 1, where both simulations have similar trends but differ in the third-year period. Run 155 shows larger fluctuations within its own trend, with a slightly higher peak value than Run 156, with a difference of $\Delta 0.05$ MPa. This difference is larger in the range of shear stress for Joint 1, with the average time series shown in Figure 8-7g. Run 155 has larger shear stresses at the peak and smaller stresses at the trough of the third-year period. This is associated with the larger deformations occurring in Slab 1, as shown through the deviatoric strain differences. However, the redistribution of stress towards the lateral fracture showed an opposite situation, as illustrated in Figure 8-7h. Run 156 induced more stress at the lateral fracture than other runs, with a difference of $\Delta 0.3$ MPa compared to Run 155. This is related to the failure propagation towards the lateral fracture in the scenario where a plastic region is close to this surveyed feature.

Incorporation of plasticity in specific regions induced larger displacements in Slab 1, closely aligning with the calculated data. This setting is capable of transferring stress and generating larger deformations in the rock mass, inducing failure in other regions that were set elastically, such as the notch area behind Slab 1 or in Slab 1 itself. Although it has been observed that plasticity in Slab 1 delivered results outside the range of measurements in erratic orientations. Based on the incremental deformation of Slab 1 and the induced shear stress at Joint 1, the plasticity could also be extended to the joint setting by varying their properties, such as stiffness, cohesion, and friction angle, throughout the simulation time. However, such a transient approach is beyond the scope of this research.

8.2.5 Localized Plasticity: Notch Section of Slab 1 and Joint 1 Strength Reduction (cohesion)

Numerically, the joint strength reduction in addition to the localized plasticity at the notch section could enhance the model outcomes to achieve an increasing trend of fracture opening (FO). The stress induced by the failure of zone elements at the toe of the Slab 1 could be distributed towards the upper part of Slab 1, loading the joint surface and inducing larger stresses on the joint plane with subsequent larger East-West displacements. Hypothetically, the strength reduction, through the cohesion weakening, would enlarge these displacements by reducing the joint contact surface, expanding the breaking of bond elements and releasing nodes to a free movement. Hence, a model to couple both effects was created, leaving the entire simulation to run until July 2023. To this end, the cohesion of Joint 1 was reduced to 0.5 MPa, which is half of the Run 156 results,

allowing the interface to slip while bonded. Run 156 is used as a base case and the current simulation is named Run 157. Both simulations are illustrated in Figure 8-8.

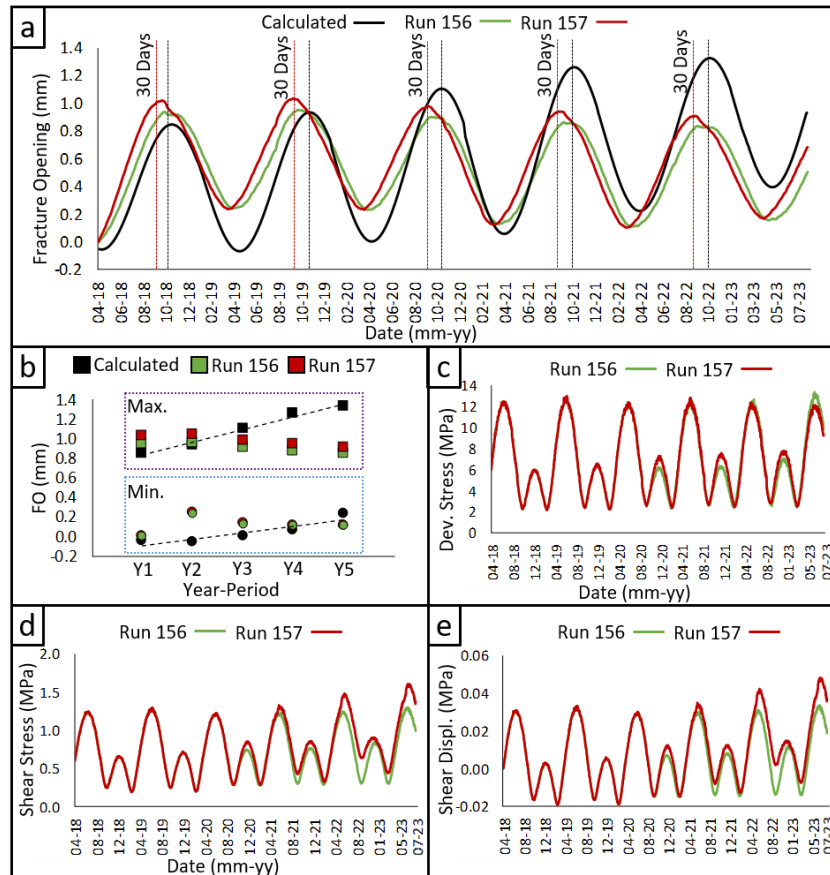


Figure 8-8: Daily average results for Run 156 and Run 157. Run 157 models the localized plasticity at the notch section and Joint 1. The simulation period extends from April 2018 to July 2023. The complete a) time-series for calculated and simulated fracture opening highlights the shift in peak values for Run 157, with black dashed lines for the peak of calculated data and red dashed lines for the peak of Run 157; whereas the b) maximum and minimum values are compared per year period. Black dashed lines between maximum and minimum values for calculated data represent a linear regression between data points. Stress plots for the average c) deviatoric stress for Slab 1 and d) shear stress on Joint 1 plane are shown as time-series. Resulting e) shear displacement of Joint 1 is compared between Run 156 and Run 157.

Variations in the joint cohesion shifted the peak value of the trend by 30 days from the calculated data peaks, as shown in Figure 8-8a, enclosed between black and red dashed lines representing peaks of calculated and Run 157 data, respectively. This shifting is consistent throughout the entire simulation time and aligns with the overall elastic adjustment from Figure 7-43. However, the magnitude of the peak is $\Delta 0.05$ mm larger than the peaks for Run 156.

Both simulation trends start with larger fracture opening values but with a decreasing trend that, by the third-year period, i.e., between April 2020 and March 2021, crosses the calculated trend to reach smaller peaks of FO consistently until the end of the simulation time. This is also seen in

the comparison between the magnitude of peaks and troughs introduced in Figure 8-8b, retrieved by year period. The maximum value tends to decrease for the simulations, whereas between simulations, Run 156 decreases at a slower rate than Run 157, visualized through the closing alignment between point data. By the fifth year period, the difference between calculated and simulation data is almost $\Delta 0.5$ mm, which is 38% of the peak value for calculated data.

Conversely, the minimum values from simulation results align better with the calculated data except for the second year period. In the second year period, the average of the simulation minimum is 0.24 mm, whereas calculated data has a lowest value of -0.1 mm. For the subsequent year periods, the simulation minimum decreases but remains greater than calculated minimums until the fifth year period when trends cross each other and calculated data start being larger than simulations. Nevertheless, the simulations also have a decreasing trend of minimums.

Analysis of the deviatoric stress for the upper section of Slab 1 revealed that stresses fluctuate between 2.5 MPa and 12.5 MPa through the simulation time, as shown in Figure 8-8c. However, differences between simulations are seen after the second year period, with larger deviatoric stress values for Run 157 in the colder months. The overall trend shows stress accumulation in Run 156 from the failure of the notch section, whereas Run 157 stress tends to decrease as part of the stress distribution towards Joint 1, since it is expected the larger displacements and bond breaking. This relates to the increment in shear stress in Run 157, depicted in Figure 8-8d. Both simulations have similar trends for shear stress fluctuations; however, Run 157 starts accumulating larger shear stress than in Run 156, with final differences of up to 0.4 MPa at the last peak value.

The shear stress results in similar trends for the shear displacements, depicted in Figure 8-8e. Run 157 is capable of generating larger shear displacements from Joint 1 in both directions. The tendency towards positive displacements, i.e., eastward movement, increases throughout simulation time but at a rate of 0.01 mm/year, contributing only 1% of the peak value of fracture opening. Variations in rock stiffness as a result of an increasing shear stress could also improve the alignment with calculated data. However, the influence in the shifting of peaks suggests that strength weakening cannot be carried out with cohesion reduction only, but requires integrating friction and tension as part of the strain softening of joints. In addition to the transient simulation, the approach that interplays the joint properties dynamically is out of the scope of this research.

8.2.6 Qualitative Strategies for Inelastic Displacements

Previous simulations helped in the understanding of the main contributing factor to align simulation results with the measured data. The analysis focused on essential features such as the notch area and the joint plane of Slab 1. Despite the deployed strategies assisted in matching displacements for at least two periods, the six-year trend did not improve throughout the simulation time to follow the measured trend of fracture opening. The analysis of maximum and minimum values per year period revealed that the displacements are not sustained in the long-term due to the model settings for static inputs, as no time-dependent rock properties.

Since the dynamic approach with the heat source as the main stress driving mechanism, the rock properties could vary with temperature fluctuations. However, it should not be understood from a direct thermal influence at a micro scale, but rather as a result of the induced damage from the induced stress fluctuation. The simulation cases showed that deviatoric stress varies largely in one annual cycle, with the potential to generate new cracks. For instance, the results from Run 156 showed a deviatoric stress maximum peak of 12 MPa for Slab 1, which overpasses the crack initiation value measured for the micritic limestone of 11.4 MPa. At the end of the simulation, deviatoric stress become larger denoting a sustained stress accumulation in the Slab 1, which rises the stress level even beyond the crack initiation threshold. This could not be associated with a GSI variation, as examined in these trials, but a degradation of the intact rock stiffness and strength as a result of the thermal cycle. Therefore, time-dependent studies of rock properties could be also tested for the current case, such as the analysis from Heap et al. (2009), Cai et al. (2004), Zhou et al. (2011), Perras and Diederichs (2016), Paraskevopoulou (2016), Huang et al. (2020), Wang et al. (2021), Liu et al. (2022).

Additionally, other constitutive models could be tested for the rock mass behaviour, such as the strain-softening-hardening approach for brittle rocks. Difficulties arise to assess the plastic strain limit for the micritic limestone, and the FLAC3D® implementation becomes challenging when using such irregular and small zones (Itasca, 2019). To overcome this challenge, the implementation through the cohesion-weakening-friction-strengthening model (CWFS) from Walton (2019) could reflect the increasing trend with the inelastic displacements. The CWFS model is suggested to be tested in sequential stages to extend the plasticity across the rock mass, with the initial focus on the notch section of Slab 1, and extending southwards to the other slabs.

The extension of plastic regions could also enhance the modelling outcomes, by redistributing larger stresses towards the upper section Slab 1 as explored in the trials. However, the stress distribution towards Slab 2 and Slab 3 could also increase the displacements eastwards. This

could build up stresses at the joint planes which can lead the Slab 1 movement. To this end, the study of the notch plasticity is key in understanding how the failed zones extend westwards, and the stress being distributed laterally and vertically. Also, the lateral fracture could be segmented to delineate the regions adjacent to the slabs, so accompanying the failure if extends over the western side of the area.

In fact, the wall of the adjacent cliff at which fracture opening value is constructed may also behave differently than the current modelling. The fracture opening from simulations is calculated as the difference between the average horizontal movement of the central part of Slab 1 minus the displacements generated at the cliff wall at the same elevation but 30 cm deeper in the rock. Rock mass stiffness and thermal inputs may vary at this point as a result of failure, which could also model a more realistic condition. This would not directly reflect the inelastic movement of the Slab 1, yet it could reveal the origin of the long-term trend.

Another approach relates to the dynamism of joint properties, as a result of stress accumulation on the plane, and the cyclic building of normal and shear stresses. These repeated cycles can lead to degradation of joint asperities, reducing the shear strength over time as suggested by Zhu (2022) and Liu et al. (2023), yet it depends on the joint condition and the rock type. Cyclic shear loading can also impact on the normal stiffness (Wang et al. 2009, Premadasa 2012) and its subsequent variation on the shear stiffness. However, the strength weakening tested in the previous Run 157 demonstrated that a reduction in cohesion increased the amount of shear stress at the joint surface, while also shifting the peak of fracture opening to 30 days earlier than the measured peak value. Hence, an integrated study with the dynamic frictional behaviour of the joints due to the cyclic shearing may deliver that frictional components decrease with cycles (e.g., Zhang et al. 2023), a non-linear behaviour for stress and stiffness (e.g., Prasetyo et al. 2017) or impacting the apparent friction angle only (e.g., Barton, 1976).

A final approach leans on the thermal inputs, due to localized fracturing and variations in the rock continuity either at micro or macro scale. This so-called thermal damage, in studies at temperatures above 100°C, can significantly alter the thermal properties, mainly reducing the thermal conductivity due to crack generation (Junique et al. 2021, Kumari et al. 2017), and impacting the thermal expansion coefficient (Li et al. 2022). This would also redistribute stresses, by creating thermal discontinuities in addition to the presence of the joints. The impact is tough to predict, whereas in some instances it can reduce the stress to stop the failure extension such as at the notch section, in other instances this reduction could lead to shorter displacements such as the joints, especially Joint 1, or the slabs.

Instances to achieve the inelastic displacements being modelled are countless, and not limited to the suggested strategies in this work. Even the exploration of other contributing factors such as microscale conditions from humidity of the micritic limestone can be also explored. However, the focus of this work is on understanding and modelling the measured data. The strategies are framing the current investigation, and providing guidelines to further tests.

8.3 Thermo-Mechanical Fatigue Analysis

The results from Run 156 were utilized to assess the model's response to stress fluctuations under transient thermal conditions. The FO magnitude from Run 156 demonstrated better alignment with the six-year modelling period compared to other simulations, while peak values corresponded well with the calculated data over time. Furthermore, the model incorporates localized plasticity at the notch section, enabling the induction and redistribution of stresses towards other features, including joints and the lateral fracture.

8.3.1 Cyclic Behaviour

The thermo-mechanical cycles are illustrated in Figure 8-9, plotted against the rock temperature. The fracture opening and rock temperature for the calculated data are depicted in Figure 8-9a for the period measured between April 2018 and March 2023. The final year, i.e., the sixth-year period, was excluded from the analysis to avoid incorporating outliers in the maximum and minimum values, as the measured data end in July 2023. The simulation cycle progresses rightwards, starting at temperatures between 20°C and 25°C. The ratio of fracture opening to rock surface temperature is 0.044 mm/°C for the calculated data and 0.025 mm/°C for the simulation. The average rate of total displacement is 1.06 mm/year for the calculated data and 0.83 mm/year for the simulation. Of these values, the reversible displacements account for 0.94 mm/year, or 90% of the total fracture opening in the calculated data, and 0.81 mm/year, which is 97% of the total displacement in Slab 1 from the simulation. This suggests that the model could potentially be enhanced by exploring new strategies for plasticity. Consequently, the largest discrepancies, nearly eightfold, are observed in the irreversible displacement rates, with 0.12 mm/year for the measured data compared to 0.014 mm/year for the simulation results.

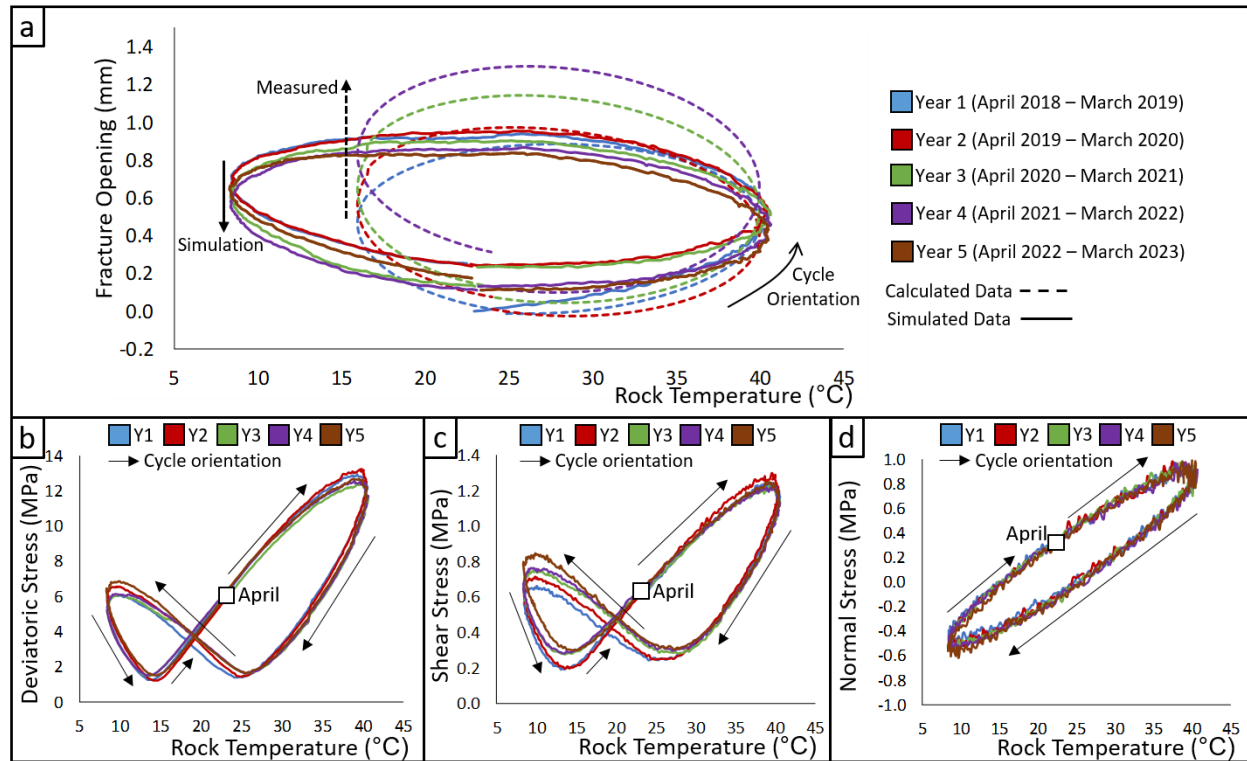


Figure 8-9: Thermo-mechanical cycles from calculated data and simulation results. Simulation Run 156 was used only for the full-year periods. This means cycles from April to March, hence 6-year period is not included in the analysis. The a) fracture opening cycles against rock temperature are plotted for both calculated and simulation data, using measurements and model results. The b) deviatoric stress cycle throughout the entire simulation time loops against rock temperature, with the full cycle closing each April. Likewise, stress cycles at the Joint 1 plane are included with the orientation of the cycle for c) shear and d) normal stresses.

As part of the observed inelastic displacements, the calculated trend shows an increase after each cycle during colder temperatures, evidenced by the broader span of the cycles compared to those in hotter temperatures. This corresponds to the peak values reached between October and November, followed by the winter season, as illustrated in Figure 8-1a. Since the fracture time series increases during hotter periods, there are no significant contrasts between these periods except when the model reaches its peak. In contrast, the modelled results indicate a reduction in fracture opening after the second year, as discussed in Section 8.2.4, deviating from the inelastic trend. Nonetheless, the range of maximum temperature and the cycle's nature suggests that displacements can be modelled and adjusted to align with the calculated data.

The average deviatoric stress for Slab 1 is derived from the central surveyed point in the upper part of the slab. The results, presented in Figure 8-9b, cover five years of simulation. The cycle's orientation is indicated with arrows, starting from April each year. The data forms a lemniscate shape, with a shorter end at the lower temperature range. At higher temperatures, stress tends to increase until the second year, then decreases and begins to accumulate from the third to the fifth

year. This is more clearly depicted at the lower temperature range, where the span between cycles widens, showing the highest value in the fifth year, implying stress accumulation due to redistribution from the notch area. It is important to note that the area beneath Slab 1 is set as plastic, with failure leading to stress redistribution towards the upper part of the slab and the lateral fracture, as discussed in Section 8.2.

Similarly, the shear stress cycles in Joint 1, depicted in Figure 8-9c, show more pronounced stress accumulation during colder temperatures. However, such significant variation is not observed in the normal stress, which cycles consistently throughout the simulation period, as shown in Figure 8-9d. Daily fluctuations are observed in the normal stress within a cycle, with the largest occurring during hotter temperatures. This is linked to the peak deviatoric stresses generated in Slab 1 and their influence on opening the joint northwards.

8.3.2 Deviatoric Stress Cycles

Given that stress accumulates and redistributes among various features in the model, the thermo-mechanical fatigue analysis focuses on the most critical elements, including the slabs, the notch, and the lateral fracture that spans the rock column. The modelling stage reported the stress tensor across all features, with particular interest in data for Slab 1, Slab 2, Slab 3, and the rock column behind Joint 3.

Deviatoric stress time-series are used to calculate yearly fluctuations, defined by alternating stress (AS) and midrange stress (MS), as introduced in Section 1.2.3. As shown in Figure 8-10, assuming a fluctuating time-series between a peak value equals to σ_a and a trough value of σ_b , the two characteristic values can be calculated. The MS represents the central value around which the time series fluctuates between two values, while AS refers to the difference between MS and the peaks or troughs, defined by Equation 8-1 and Equation 8-2.

$$MS = \frac{(\sigma_a + \sigma_b)}{2} + \sigma_a \quad \text{Equation 8-1}$$

$$AS = \frac{(\sigma_b - \sigma_a)}{2} \quad \text{Equation 8-2}$$

These characteristic values are plotted in the Goodman's diagram (1899) for deviatoric stress, displaying MS and AS per year and feature, as shown in Figure 8-10a. Slab 1 reaches a maximum AS of 6 MPa and an MS of 8.5 MPa, with the other features following a trend in the lower stress range, below AS of 2.5 MPa and MS of 6 MPa. Slab 3 and the column exhibit minor fluctuations

in deviatoric stress, with AS values under 1 MPa. This corresponds to the minimal temperature fluctuation at these points, resulting in less stress induced by thermal conditions.

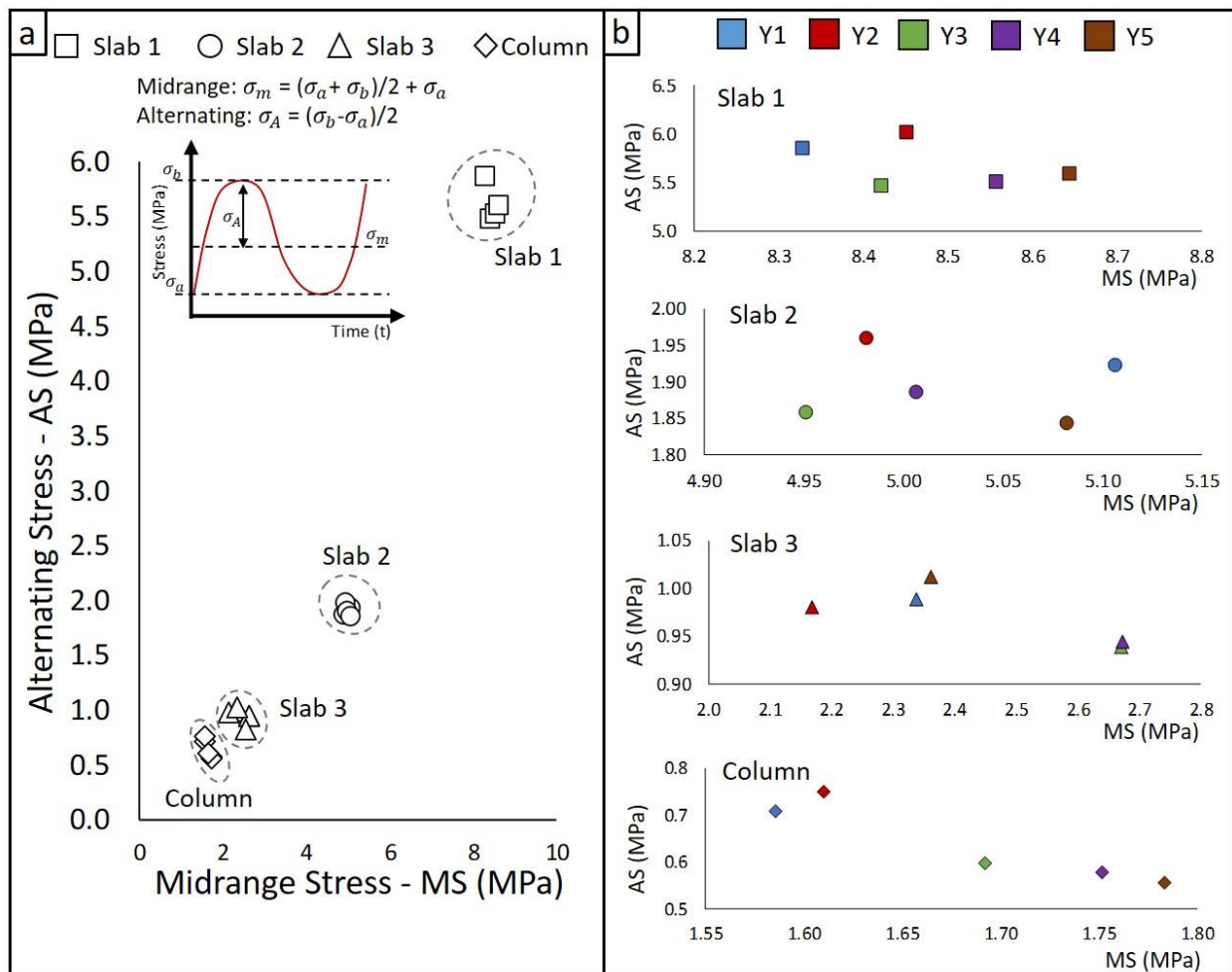


Figure 8-10: Deviatoric stress generated from thermal fluctuations at Slab 1, Slab 2, Slab 3 and the rock column behind Joint 3 are plotted in the alternating-midrange stress plot, highlighting the cyclic behaviour of features. The a) generalized diagram including all features reminds the calculation of the entries to this diagram from the deviatoric stress time-series. The b) dynamic throughout five simulated years are detailed for each region with a best fitting line (dashed line) in between data points to indicate when a decreasing trend for midrange stress increments exists.

The data are also presented temporally by feature in Figure 8-10b, with a colour legend indicating the year in which the range of deviatoric stress fluctuates. All features show a decreasing trend in both AS and MS, even in Slab 2, which displays a flatter trend compared to other features. This supports the concept that AS is capped by the MS value; the greater the MS, the smaller the AS.

The temporal sequence of deviatoric stress values for Slab 1 corresponds with the reduction in AS as simulation time progresses, indicating an incremental stress distribution. However, data from Slab 2 do not reveal a clear trend, as AS and MS values do not align consistently with the simulation timeline. This may be due to the range of stress variations being overly sensitive to

minor stress fluctuations or potentially influenced by small perturbations from the shear stress accumulation in Joint 1 (Figure 8-9c). Similarly, Slab 3 and the column do not follow a clear sequence, reporting only a short range of deviatoric stresses, with $\Delta 0.07$ MPa for AS and $\Delta 0.4$ MPa for MS. At the current stress scale for the rock mass, the sensitivity and calculation of the plot inputs could lead to misinterpretations of the data.

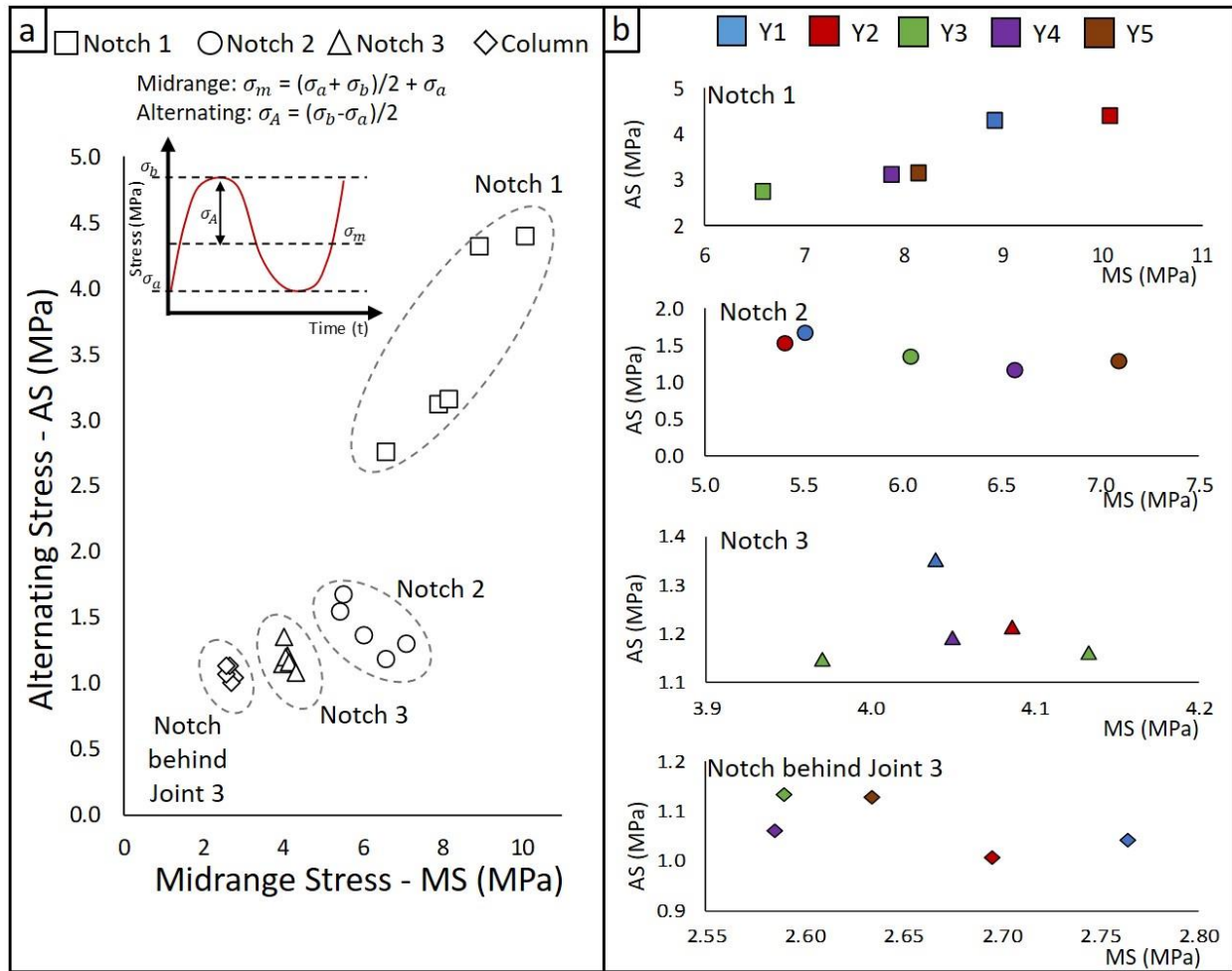


Figure 8-11: Deviatoric stress generated from thermal fluctuations at Notch 1, Notch 2, Notch 3 and the notch behind Joint 3 are plotted in the alternating-midrange stress plot, highlighting the cyclic behaviour of features. The a) generalized diagram including all features reminds the calculation of the entries to this diagram from the deviatoric stress time-series. The b) dynamic throughout five simulated years are detailed for each region with a best fitting line (dashed line) in between data points to indicate when a decreasing trend for midrange stress increments exists.

Similar plots were generated for the time series of deviatoric stress in the notch area, specifically the lower part of the rock column. The general plot, presented in Figure 8-11a, shows the results for Notch 1, i.e., the notch area in Slab 1, which displays the highest AS and MS values. It is important to note that Notch 1 is modelled as plastic in the simulation, so the deviatoric stress accumulation may follow different patterns compared to other areas defined as elastic. For

example, the data are divided into two subgroups with distinct AS and MS values, while the remaining groups are closely clustered within small ranges of stress fluctuation.

Individual feature plots are shown in Figure 8-11b, where it can be observed that Notch 1 displays an increasing alignment of data that does not follow the previously noted decreasing trend. This is likely due to the plasticity settings in the area, which may result in a composite state after actual failure is reached. The initial stress state begins in the first year, redistributes by the second year, when failure may have occurred, resulting in a new stress state that pushes the AS and MS values down to balance the overall rock mass. As new deviatoric stresses accumulate in the region, the time series increase with simulation time, producing new AS and MS values until further failure re-adjusts the stress state. Notch 2 shows better alignment with the stress sequence, although this area was modelled as elastic and no failure is reported. Notch 3 and the notch behind Joint 3 exhibit a narrow range of AS and MS values, leading to susceptible plots that explain the low alignment with the sequencing. Additionally, these features are less impacted by thermal fluctuations due to their position within the low-temperature boundary region.

The lateral fracture was examined at several locations, with the data represented in Figure 8-12a. The points adjacent to Slab 1 (LF1), Slab 2 (LF2), Slab 3 (LF3), and the rock column behind Joint 3 (LF4) were specifically analyzed. As Notch 1 is set as plastic, failure in the region redistributes stresses towards Joint 1, the upper part of Slab 1, and the lateral fracture. Therefore, stress fluctuations may be influenced by both thermal changes and notch failure. The reported values are generally larger than those of other analyzed features, as this region acts as a rock bridge between the column and the adjacent cliff, transferring stresses across the structure. The data show that most features cluster within a narrow range of deviatoric stress, except for LF1, which fluctuates between 8 MPa to 10 MPa for MS, and 2.5 MPa to 3.5 MPa for AS. LF1 experiences the greatest deviatoric stress values, being the most exposed to thermal cycles.

The sequencing of simulation results is depicted in Figure 8-12b. LF1 shows an increasing linear trend among the data points, contrary to the behaviour observed at other locations. This is linked to stress distribution resulting from Notch 1 failure, which aligns during the first and second years with a narrow fluctuation range, varying by $\Delta 1$ MPa in both AS and MS values. Deviatoric stress subsequently increases from this state, though at a slower rate than the initial change.

Regions such as LF2, LF3, and LF4 exhibit better alignment with the sequencing, except in the fifth-year period. Despite the potential sensitivity of results when registering narrow stress ranges, this alignment may reflect the integrated processes within the rock column that impact the lateral

fracture, which serves as a rock bridge to the cliff. The results for the fifth year may be associated with the region's elasticity and potential cracking, which introduces a new stress state not fully captured under the current modelling parameters.

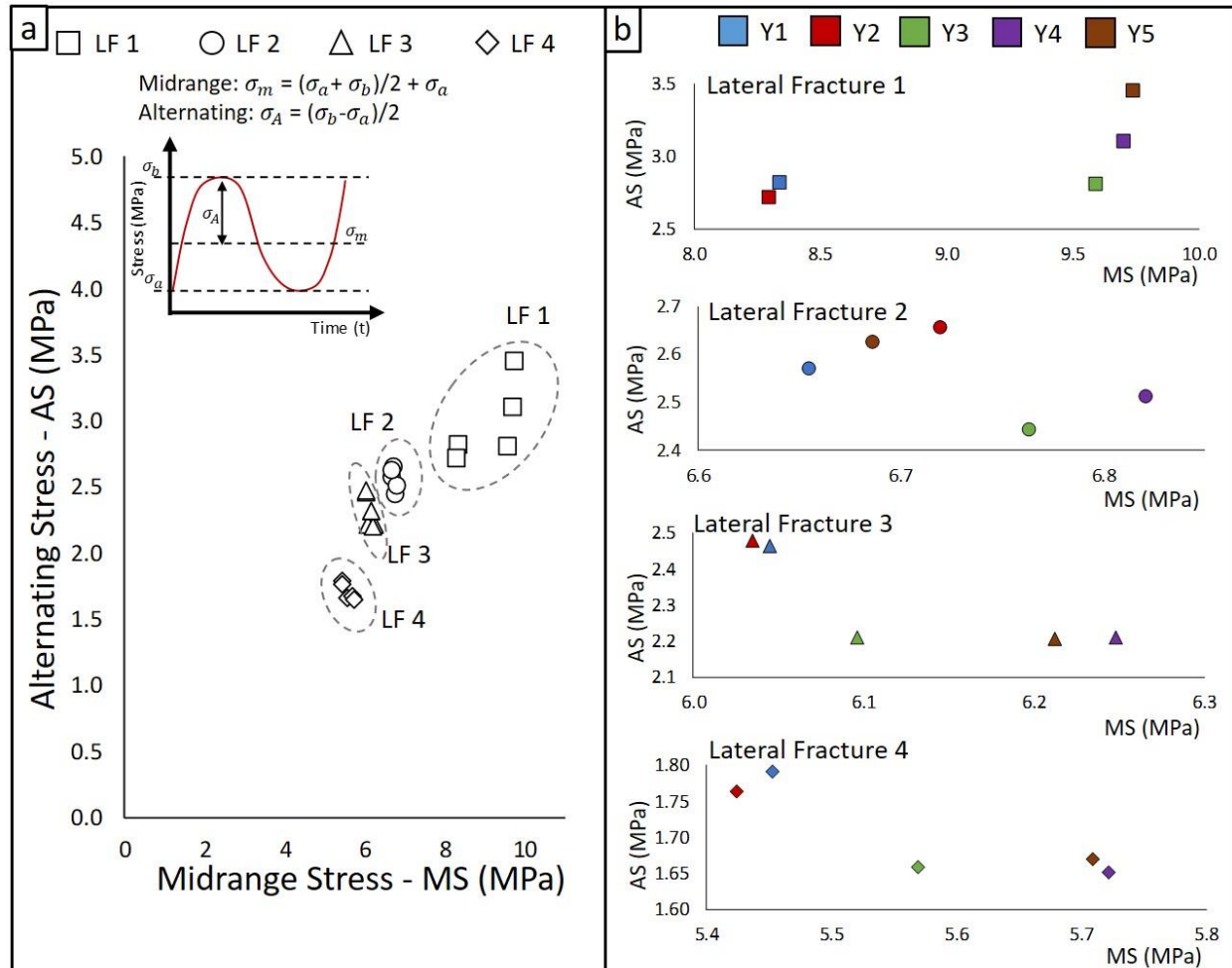


Figure 8-12: Deviatoric stress generated from thermal fluctuations in the lateral fracture at several locations such as: adjacent to Slab 1 (LF1), adjacent to Slab 2 (LF2), adjacent to Slab 3 (LF3) and adjacent the rock column behind Joint 3 (LF4). Results are plotted in the alternating-midrange stress plot, highlighting the cyclic behaviour of features. The a) generalized diagram including all features reminds the calculation of the entries to this diagram from the deviatoric stress time-series. The b) dynamic throughout five simulated years are detailed for each region with a best fitting line (dashed line) in between data points to indicate when a decreasing trend for midrange stress increments exists.

8.3.3 Analytical Description of Crack Growth

The Goodman's diagram (1899) for alternating (AS) and midrange (MS) stresses in the time-series of deviatoric stress at various features indicated that certain regions of the model experienced sustained stress increases, particularly in the slab, notch, and lateral fracture associated with Joint 1. These regions are the most exposed to temperature fluctuations and are interconnected through localized failure at the toe of Slab 1. The variation in AS and MS after each cycle is explained by stress distribution, although not all features exhibit failure due to their elastic settings.

As discussed in Section 3.5, regarding the analytical modelling and analysis of crack growth induced by thermal stresses, changes in stress can be associated with criteria that limit the AS and MS that a specific rock mass configuration can withstand. Hypothetically, after each cycle, the rock mass may approach these limits, leading to stress redistribution towards less-loaded features. This redistribution can generate local cracks that may extend into long fractures over time, eventually leading to the failure of the rock mass. To better illustrate this dynamic transition, Figure 8-13 depicts the temporal relationship of the stress states in the most critical features.

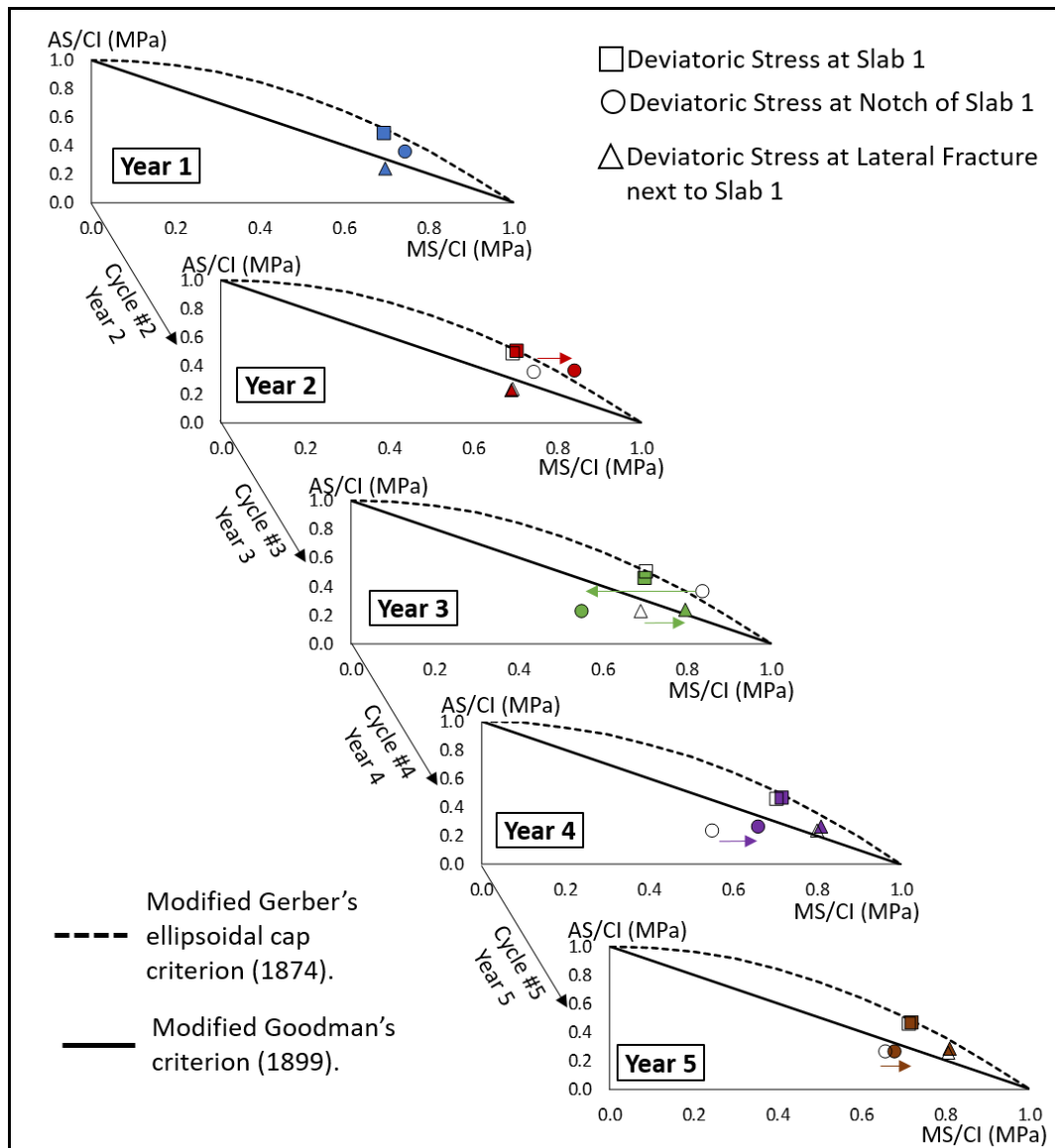


Figure 8-13: Alternating-midrange stress diagram normalized by the crack initiation value (CI), including the Goodman (1899) and Gerber (1874) cap criterion for transient stresses acting on the rock mass at the most exposed features such as the Slab 1, Notch 1 and the Lateral Fracture adjacent to Slab 1. Diagrams include the current state (coloured symbol) and the previous state (blank symbol) to show the dynamic of the stress state when thermal loads are acting within a full cycle. Hence, each diagram represents the state of a specific year. For comparison purposes, first-year period was used as the initial state.

Gerber (1874) proposed a curved line to define a stress limit, enclosing all stress states under repeated loading of a material. Points below this line can experience a defined range of AS and MS stresses without reaching failure. Similarly, Goodman (1899) proposed a straight line to establish this limit. For the purpose of this research, the fatigue limit is marked as a zone between the two envelopes rather than a sharp boundary. In engineering materials, endurance and yielding stress thresholds are typically used to plot these criteria. However, in brittle materials like the tested rock mass, the limit is assumed to be governed by deviatoric stress and the crack initiation threshold (CI). The ratio of deviatoric stress to CI is crucial for guiding the initial fracturing of the region (Diederichs 2007; Perras and Diederichs 2016). Therefore, the Goodman diagram is adapted to AS and MS axes normalized by the CI value. As reported in Table 5-7, the average CI value for micritic limestone under parallel load is 11.4 MPa, which is used as an average limit to describe dynamic loading with maximum AS/CI and MS/CI ratios of 1.

The first-year period is taken as the initial loading condition, with data for Slab 1 and Notch 1 falling within the two failure criteria. After the second cycle, stress is redistributed, leading to the state observed in year period 2. Small fluctuations are seen in Slab 1 and Lateral Fracture 1, while Notch 1 exceeds both the Gerber and Goodman limits, resulting in failure, as discussed in Section 8.2.4. This failure leads to subsequent stress redistribution to other features.

In the third-year period, the stress parameters at Notch 1 decrease from MS/CI of 0.84 to 0.55, and from AS/CI of 0.37 to 0.23. Slab 1 also sees a reduction in deviatoric stress but remains between the two failure limits. In contrast, deviatoric stress in Lateral Fracture 1 increases, reaching the Goodman criterion, suggesting potential failure in this region. After the fourth cycle, a new stress configuration at Notch 1 drives the parameters forward, causing similar effects in Slab 1 and Lateral Fracture 1. These two features remain between the failure criteria, indicating the possibility of new crack formation.

In the final cycle, leading to the fifth-year period, the stresses at Notch 1 show a similar AS/CI value as the previous year, with an increase in midrange stress, implying stress accumulation in the area that could lead to new fracturing. The thresholds for both axes have been assumed constant throughout the analysis; however, new crack formation and evolving stress conditions could alter these thresholds. This is important because Notch 1 could have failed under different AS/CI-MS/CI conditions due to changes in the limits.

The analysis for Slab 1 and Lateral Fracture 1 suggests that if failure had been permitted in these regions in the model, the resulting stress distribution would have differed, potentially redistributing

stress toward the features behind Joint 1 and leading to larger fracture openings. However, in all plastic simulations where Slab 1 was modeled using the Hoek-Brown criterion, the resulting displacements were too large to compare with actual measurements. This observation is consistent with the behaviour of Slab 1, as the average deviatoric stress remained within the failure zone throughout the simulation years.

The plot aids in predicting the long-term stress state of the rock mass. For example, the fifth-year period represents the current stress condition, with all prior AS/CI and MS/CI instances dominated by the current mechanical condition. Future instances of these parameters will depend on the current condition's response to thermal perturbations. Numerically, Notch 1 has an AS/CI of 0.26 and an MS/CI of 0.68. If thermal fluctuations increase the MS/CI value to 0.8, indicating an upward trend in deviatoric stress, then the maximum AS/CI would be 0.2. In practical terms, this means that deviatoric stress fluctuations must remain between 6.8 MPa and 11.4 MPa to prevent new cracks or failures in the region. Physically, this sets a limit on the temperature fluctuations the rock can withstand unless rehabilitation or rock support increases the rock mass strength. This would shift the failure envelopes, allowing for other combinations of alternating and midrange stresses, enabling the system to endure larger fluctuations without failure.

8.3.4 Overview of the rock column movement due to Slab 1 fracture growth

The integrated movement of the rock mass is described by the horizontal and vertical displacements of the rock column at the end of the simulation period, i.e., July 2023. The axes are oriented such that displacements in the x-direction are eastward, in the y-direction are northward, and in the z-direction move along the elevation. The impacts of thermally driven stresses on the total displacements must be interpreted in accordance with the thermal boundaries, since movements of certain features could be influenced by the expansion of zones rather than actual displacement. However, sustained deformation is observed in specific regions such as the slabs and notch, as shown in Figure 8-14. It is worth mentioning that in some instances, a different legend has been used to differentiate the displacement of Notch 1 from the rest of the rock mass, as the elements have failed. Additionally, results are plotted to the end of the simulation, reflecting nighttime and therefore the cooling interval of the daily fluctuation.

Horizontal displacements in the East-West profile are oriented similarly to the displacement sensor used to measure fracture opening, as shown in Figure 8-14a. Due to temperature contrasts, Slab 1 shows a part that moves eastward and a side that moves westward, associated with the thermal boundary differences. However, the range of displacement is approximately $\Delta 2$ mm in each direction. As previously mentioned, the displacement vectors at the notch section ranged from 2.6

mm to 26 mm due to the failed zones, yet the vector indicates the combined displacements from all axes.

The vertical displacements also ranged between -2 mm and 2 mm, with negative values concentrated only in the upper corner of the notch, associated with a detachment of zones as illustrated in Figure 8-14b. The other areas show a positive displacement due to stress relaxation from the cooling part of the cycle. The upper part of Slab 1 shows a potential uplifting that may be associated with a toppling mechanism. Nevertheless, the notch area beyond the failed area ranged between -0.5 mm and 0.5 mm for vertical displacements, which does not indicate a preferential movement when considering the entire slab.

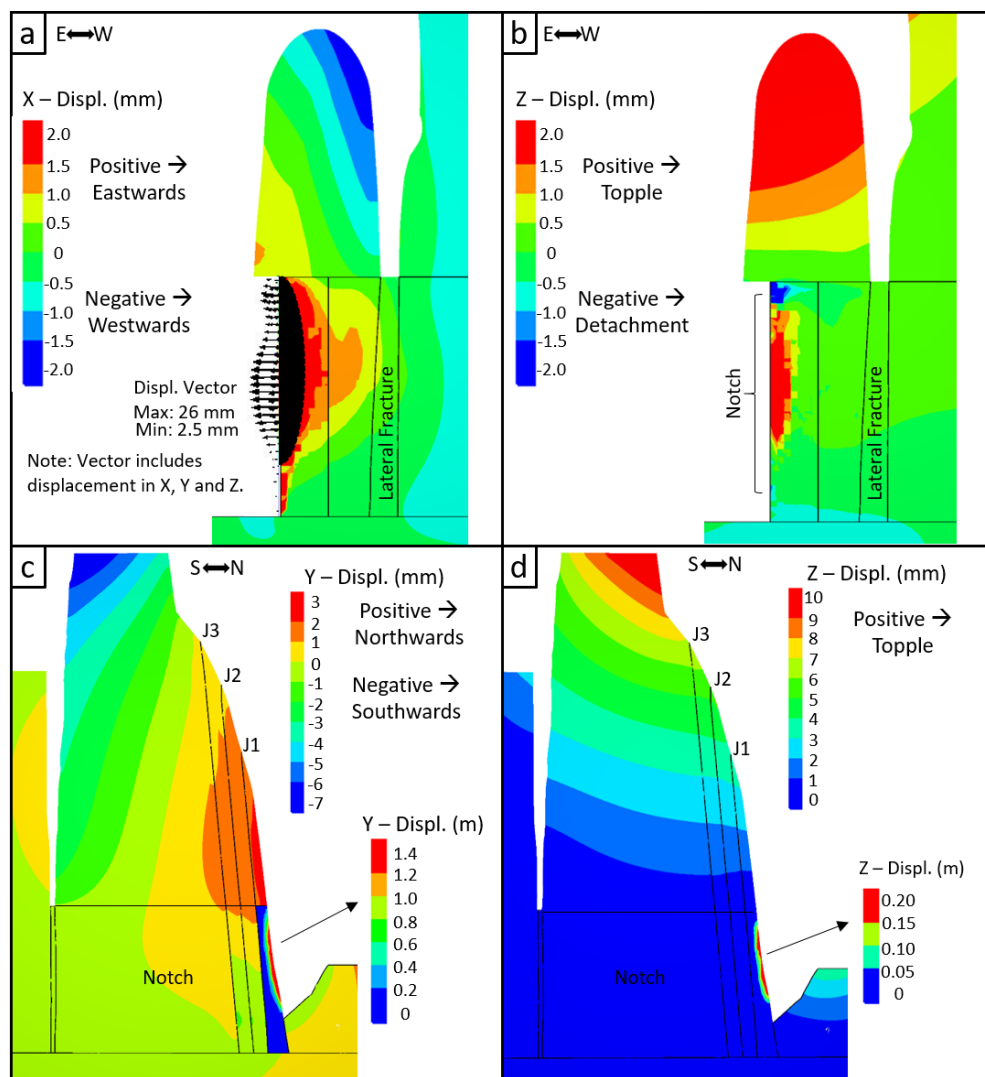


Figure 8-14: Displacement of rock column as a result of thermo-mechanical simulations by July 2023. Illustration of a) horizontal displacement in x axis, oriented East-West; and b) vertical displacement in Slab 1 section. The North-South cross section aids in showing the c) horizontal in y axis and d) vertical displacements, including the location of joints and a different colour legend for the plastic region at the notch section under Slab 1.

Horizontal displacements in the North-South orientation are the largest for Slab 1, with a maximum of 3 mm northwards, as shown in Figure 8-14c. The notch area shows displacements in the range of meters, associated with the failed zones that are depicted as a reference only; these are not realistic for the thermo-mechanical displacements but rather represent the collapsed sections. The back of the column has displacements southwards, with the top of the column reaching up to 7 mm. Differences across joints are reported as part of the mechanical properties of the interfaces that redistribute stress and mobilize deformations, with displacement values ranging between 1 mm and 2 mm at the central part, limited by the boundary with the notch. Nevertheless, the base of the column ranges between southwards and northwards displacements, with an overall range of $\Delta 1$ mm.

Vertical displacements are also illustrated in the North-South profile in Figure 8-14d, with the highest values at the top of the rock column, associated with the top region's thermal boundaries. The displacements seem to stabilize by decreasing with elevation, so when crossing Slab 1, these values are not larger than 2 mm. This supports the idea that the reported displacements are part of the stress relaxation due to the cooling of the rock mass. Similar to the horizontal displacements at the notch section, a different scale was used to show the displacements of the failed area, with values up to 200 mm, whereas the rest of the notch has negligible vertical displacements.

The overall orientation of displacements indicates that Slab 1 is moving to the North-East, primarily due to the deterioration of Notch 1. Slab 2 exhibits similar trends, though Notch 2 remains intact; this movement is sustained by the shearing mechanisms and the dipping angle of the joints. Under other modelling scenarios the failure of Notch 2 could be reached and compared to the current on-site conditions, as depicted in Figure 7-3. These observations underscore the critical need for protective measures to prevent notch erosion, which is not solely caused by rainfall or excavations, as is commonly studied for the Valley of the Kings, but also by the combined effects of thermal stresses that impose a fluctuating load on this region of the rock mass. According to the Goodman diagram and the thermo-mechanical fatigue criterion, fluctuations in mechanical and thermal loads result in different stress states and potentially alter the strength properties of the rock. Finally, strategies such as minimizing thermal fluctuations and enhancing rock strength are recommended to reduce irreversible (inelastic) fracture opening trends. An effective approach includes constructing concrete walls at the entrance of tombs in KV, which helps to structurally support the toe of the column, whereas this type of construction may align with the inherent restrictions of the site to not alter the scenery and to preserve this cultural site.

8.4 Lessons Learnt on Fracture Growth under Thermo-Mechanical Fatigue

This chapter explores various approaches for modelling inelastic displacements reported from the rock column above tomb KV42. It builds on the model construction and thermo-mechanical elastic simulations with plastic joints detailed in CHAPTER 7, aiming to develop a strategy that aligns better with both modeled and measured data.

Elastic and inelastic, i.e., reversible and irreversible, displacements were differentiated by overlapping current and previous measured data for annual differences. The simulation time was divided into yearly periods, covering data from April to March, which aligns with the measurement start date. Fracture opening and rock surface temperature were analyzed to define the cyclic behaviour of the column, using the most recent data from April 2018 to July 2023.

The strategies for modelling inelastic displacements aimed to extend the base case simulation from 12 to 67 months, encompassing the entire monitored period. The goal was to match the trend of fracture opening, which increases with time after each cycle. Nearly 100 models were run and analyzed for thermo-mechanical simulations, with the 50 most relevant models grouped into elastic, plastic, and elastic with localized plasticity categories.

Plasticity in the rock mass was incorporated under different conditions. Initial tests compared dynamic reductions in joint stiffness as a hypothetical result of shear and normal stress accumulation. These results indicated that a significant reduction in joint stiffness, by two orders of magnitude, could contribute up to 10% to the resulting fracture opening. This approach potentially matched measured trends but proved geotechnically infeasible without joint failure due to increased shear and normal stress.

A second approach involved reducing the rock mass GSI to lower rock mass properties. Comparative analysis showed that deviatoric strain accumulates in Slab 1, which could be linked to crack growth. Volumetric strains fluctuated consistently between intervals, suggesting that incorporating dilation into strength parameters could account for volumetric changes. To differentiate the impact of failure on fracture opening, an elastic approach was employed, examining the notch and lateral fracture separately. Results indicated that Notch 1, a region in Slab 1, had the highest impact on rock mass deformation by accumulating deviatoric stresses in both Slab 1 and the lateral fracture.

Localized plasticity was applied to the notch section in Slab 1, inducing larger fracture openings than the elastic solution. This localized plasticity redistributed stress to Slab 1 and the lateral fracture, increasing shear stress in Joint 1 and resulting in larger shear displacements. This

suggested potential failure at certain nodes of Joint 1. A final trial reducing joint cohesion showed that an integrated study of joint strength inputs—cohesion, friction, and tension—was needed to avoid discrepancies between measured and simulated fracture openings. Such an analysis was beyond the scope of this research and was recommended for future study.

Qualitative strategies were also suggested to improve modelling inelastic displacements, including studying strain softening-hardening of rock mass inputs. Expanding plastic regions to include the entire notch, part of the lateral fracture, and other slabs under a different constitutive model could be beneficial. Additionally, analyzing thermal properties with new cracks at temperatures below 100°C, as well as examining the cliff wall where fracture opening is referenced, could provide further insights. A study of joint properties under increased shear and normal stresses would also enhance the accuracy of the results.

Using simulated data from Run 156, stress analysis aimed to verify the cyclic behaviour of measured data with fracture opening and rock surface temperature cycles. The average measured data rate was 0.044 mm/°C, while the simulated average was 0.025 mm/°C for the entire period. The average total displacement rate was 1.06 mm/year for measured data and 0.83 mm/year for simulation, with 90% and 97% of these rates defining reversible displacements, respectively. The 2D model showed a ratio of 0.03 mm/°C and a rate of 0.8 mm/year for reversible displacements, based on a shorter 37-month simulation.

Deviatoric stress results plotted against temperature demonstrated cyclic behaviour varying throughout the modelling time. Trends increased during the first two years, then decayed before increasing again from the fourth-year period onward. Cycles for slabs, the notch, and lateral fractures were illustrated in Goodman's diagram (1899) for alternating and midrange stress. This diagram provided insights into the stress evolution for key features like Slab 1, Notch 1, and Lateral Fracture 1.

The analytical description of crack growth utilized relevant features to illustrate how stress states change over time under temperature fluctuations without reaching failure. A failure criterion was adopted, using the ratio between deviatoric stress and crack initiation stress threshold for both axes, limiting combinations of midrange and alternating stress. The diagram illustrated current and past states, showing how stress distribution shifts features to new states that may lead to failure due to temperature fluctuations. This approach aids in predicting future rock mass conditions and assessing the impact of enhancing the rock mass to shift the failure criterion.

It is important to note that, for the purpose of exemplifying the fatigue limit, a fixed crack initiation value of 11.4 MPa was used. This value aligns with the average reported by Alcaíno-Olivares et al. (2022) for samples loaded parallel to existing bedding planes. However, crack initiation stress can range from 9.7 to 33 MPa, with higher values observed in samples loaded perpendicular to bedding planes, averaging 23.8 MPa. If the perpendicular average of 23.8 MPa had been used, the conclusions would have shifted: during the five cycles, all features would remain within the unfatigued zone, varying with similar forward and backward movements relative to the fatigue limits, but remaining roughly halfway from the fatigue zone. However, since the σ_1 stress orientation is subhorizontal and closely aligned with the orientation of bedding planes, the values from parallel tests more accurately reflect expected crack initiation behavior. Thus, the measured range of 9.7 to 13.1 MPa, with an average of 11.4 MPa, more appropriately represents the crack initiation stress threshold for thermo-mechanical fatigue.

Implementing these strategies and utilizing Goodman's diagram (1899) could improve alignment with measured data and enhance the prediction of rock mass behaviour under thermo-mechanical fatigue. The presented strategies offer a foundation for studying rock mass evolution through thermo-mechanical fatigue, illustrating the ultimate state where no fatigue is allowed. This implies that if deviatoric stress midrange reaches a certain high threshold, no fluctuations or perturbations are permissible without causing failure. The approach can be tested in different scenarios to explain the evaluation of the thermo-mechanical fatigue.

CHAPTER 9 CONCLUSIONS

The study of thermo-mechanical fatigue in jointed rock masses has advanced significantly over recent decades, facilitated by improved site access and advanced monitoring systems. These systems enable simultaneous tracking of environmental conditions and rock mass responses. Despite these advancements, challenges remain in understanding the driving mechanisms and interactions between discontinuities and intact rock properties. There is no single model that fully encompasses these observations to predict rock mass behaviour accurately.

Current literature points out that thermo-mechanical fatigue can occur across a variety of lithologies, morphologies, and environmental conditions. Data analysis suggests that cycles of opening and closing of fractures affected by temperature fluctuations, in terms of their frequency and magnitude, are site-specific. These site-specific conditions are well documented in this work with their implications at formulating numerical simulations. For instance, the solar patterns, the dynamism of thermal boundaries and the impact of joints on temperature conduction were explored. Monitoring system resolution and device functioning were reported, allowing the comparison with data from other sites; as well as delivering a long-term testing at rock mass scale that exhibits positive trends of displacements, associated with irreversible displacements.

The principles underlying the behaviour of rock masses can be systematically extended or adapted to encompass a variety of rock types and engineering construction projects, including concrete design frameworks. A comprehensive consideration of thermal and mechanical properties, discontinuity orientations, characteristics conducive to subcritical conditions, and fracture patterns enables the calculation of stress tensors through numerical modelling. This methodology facilitates the derivation of deviatoric stress values applicable to Goodman's diagram (1899). The mechanics of crack initiation and propagation, instigated by repeated thermal cycling and fatigue mechanisms, exhibits applicability across diverse rock types, albeit necessitating contextual adjustments. For instance, lithologies exhibiting larger thermal expansion, such as sandstones, may manifest more pronounced fatigue effects relative to those with lower thermal expansion coefficients, such as basalts; notwithstanding, the fundamental mechanics of fatigue remain consistent.

The phenomenon of thermo-mechanical fatigue remains underexplored within the context of structural design pertaining to rock masses. This research endeavours to elucidate the processes of fracture generation within rock masses and, by extension, the implications for geological engineering designs that may experience altered stability conditions as a consequence of these geological changes. This is particularly salient for rock-cut constructions in ancient edifications,

wherein the propagation of fractures or the emergence of new cracks due to environmental cycles is critical to the overall stability of the design; notable examples include archaeological sites such as the Valley of the Kings. An integrated analysis of the evolving stress state within rock masses serves as an essential foundational approach to elucidate the stress fluctuations associated with potential failure events. Thus, the research framework extends from a unique site investigation to complex numerical modelling, thereby facilitating the simplification of complex geological scenarios to accurately predict the failure modes of shallow rock surfaces.

From a material science perspective, the behaviour of aggregates and the cementitious matrix under thermal stress can be examined in a manner analogous to that of rock masses, incorporating several key considerations. For instance, the thermal expansion disparity between aggregates engenders internal stresses attributable to uneven deformation patterns, a phenomenon that similarly manifests in cementitious materials augmented with steel reinforcement. Much like rock masses, the thermal gradients resulting in fatigue can culminate in time-dependent deformations and potential creep behaviour. However, substantial distinctions between natural rock masses and engineered materials arise concerning porosity and microstructural attributes, which may engender disparate crack initiation stress thresholds, thereby linking the material properties of strength and ductility to the mechanisms of fatigue failure.

Furthermore, the preliminary investigation into specific conditions facilitating crack propagation under temperature cycling has not yet been comprehensively addressed, indicating a need for theoretical exploration via Goodman's diagram (1899).

9.1 Summary of Research

The objective of this dissertation was to understand the role of rock surface temperature fluctuation in the resulting reversible and irreversible displacements of a shallow bedrock. Two sites were instrumented and presented in this study from different geological and environmental conditions, deploying a similar monitoring system. The first site in the Finish Archipelago, Långören Island (Northern Europe) served as a first approach to study the thermo-mechanical fatigue in near-surface environments, in a microcline granite under continental-humid ambient conditions. The second site in the Valley of the Kings, Egypt (Northern Africa) was the focus of this research due to capability to isolate the thermal fluctuations as temperature changes with no effect of water, in a micritic limestone with a hot-desert climate.

At both research sites, various additional mechanisms could potentially contribute to crack growth, including rainfall, humidity cycles, natural biological processes, mineral growth, and human

interaction. However, isolating the specific impact of temperature in outdoor settings proves to be challenging, as neglecting the influence of these concurrent processes may lead to oversimplification. For instance, rainfall can induce hydraulic pressure within cracks, while humidity may promote chemical weathering and the hydration of hydrophilic minerals, potentially causing mineral expansion that leads to fracturing or, conversely, shrinking of the rock. Including such factors in the analysis would not only complicate the failure mechanisms but would also make it more difficult to attribute crack growth solely to thermo-mechanical fatigue.

Additionally, long-term thermo-mechanical fatigue typically involves cyclic processes that occur annually, but daily cycles are also significant and contribute to the overall fatigue effects. These daily cycles provide a more observable and definable framework compared to factors like rainfall or mineral growth, which may take significantly longer to show clear cyclic effects or impacts. By focusing on thermal cycling, simplified models were developed, yielding results that were more comprehensible and reproducible. Introducing multivariable models that incorporate these additional mechanisms would have introduced greater uncertainty and required more complex datasets, which were not readily available or accurately measured. Moreover, such models often entail more intricate modelling, as some mechanisms, such as mineral growth and healing, cannot be directly coupled using existing models. This added complexity increases computational demands and time, potentially reducing the clarity and interpretability of the results.

Therefore, specific objectives guiding this research, which are detailed with their conclusions as follows:

1. To undertake a comprehensive analysis of the geological, geotechnical and climatic characteristics of the designated sites, with particular emphasis on identifying factors that could potentially exacerbate thermo-mechanical fatigue cracking.

Information of the sites were gathered from the literature and the different field campaigns conducted in each site. During the extension of this doctoral study, two field campaigns were conducted in Långören Island (August 2018, March 2019) and three fieldworks were carried out in the Valley of the Kings (February 2019, February 2020, February 2022). At both sites, the campaigns were aimed to characterise the morphology and the geological structures present in the rock mass and its surrounding. Structures such as joints and faults were recognized at the site, and characterized in the studied rock mass. Also a mapping of new structures was introduced in this work whilst tracking them annually for the case of Långören Island. For the Egyptian case,

old photographic registers were collected from the Metropolitan Museum of Art (New York, USA) to compare past and current state of the rock column.

Thermal inspections were carried out on-site, using the solar path and shade patterns to identify thermal boundaries, which were later verified with image data. Climatic characterization involved modelling data and measurements from nearby weather stations. Time-series of environmental conditions were compiled to validate measurements and assess past climatic conditions experienced by the rock masses.

Laboratory tests were performed on a cored sample from Långören Island, including wave speed measurements and tensile strength tests. In the Valley of the Kings, due to limited literature on Egyptian rock properties, a comprehensive laboratory program was conducted at South Valley University in Qena, Egypt. This program tested the geotechnical and thermal properties of the rock, revealing the strength limits and anisotropic behaviour of the intact rock, particularly due to bedding planes. Additional tests were conducted on other rock units from the Thebes Formation, including marly limestone, micritic limestone and silicified limestone; and argillaceous limestone from the Esna Shale formation. The results were compared to literature values from similar rock units at other locations. Strain measurements during UCS tests were used to determine the crack initiation threshold, which is crucial for predicting crack generation under thermo-mechanical fatigue.

2. Documentation and evaluation of instrumentation performance and data recording at the site, aiming to identify the factors and conditions likely to induce cyclic thermal deformations and eventual failure of rock masses.

The monitoring system used in this study is detailed, including its limitations and sensor installations. It comprised a dendrometer serving as a crack meter, a weather station with a rock temperature sensor, and an infrared camera at the Valley of the Kings. At Långören Island, additional temperature sensors were deployed at various vertical depths in the rock mass. The system was maintained during each field campaign. Data collected were processed, cleaned, and filled for missing values to create time-series data comparable with other sources. This validation helped highlight site-specific context that could explain particular values and trends.

Climatic data were analyzed to determine rock surface temperatures in specific regions, characterizing thermal boundary values. Långören Island featured a dome-shaped bedrock with low curvature, simplifying thermal boundary definitions. In contrast, thermal boundaries in the

Valley of the Kings were defined using an infrared thermographic survey over a year, producing temperature contrast images that revealed three main thermal regions cycling throughout the year.

Thermal cycles were analyzed alongside measured fracture openings, or crack apertures. At Långören Island, crack aperture was recorded as the opening of a horizontal slab hypothetically lifted by thermal fluctuations, relative to a non-fractured rock portion. In the Valley of the Kings, fracture opening referred to the movement of a vertical slab relative to an opposite cliff wall, connected by a rock bridge with a lateral fracture.

Both crack aperture and fracture opening were examined as functions of temperature, identifying elastic (reversible) and inelastic (irreversible) displacements throughout the thermal cycle. In Egypt, solar radiation, wind speed, and wind direction had the greatest impact on rock surface temperature, while in Långören Island, solar radiation and air humidity were the most influential factors. Irreversible displacements were linked to crack or fracture expansion, potentially advancing subcritical states in the rock mass and, in some regions, progressing toward ultimate failure.

The deformation ratios for Långören Island and the Valley of the Kings were determined to be 0.04 mm/°C and 0.05 mm/°C, respectively. While these ratios are relatively low on a larger thermo-mechanical scale, they reflect the cumulative effects of low-temperature thermo-mechanical fatigue (below 100°C). Contributing factors include the number of thermal cycles, moisture content, and the presence of pre-existing microcracks, which vary between the two sites. Additionally, the deformation ratios are influenced by the geometry of the problem, as both cases focus on single cracks located near the surface. In Långören Island, despite the low average thermal stresses, the site experienced visible and active crack growth during specific conditions, suggesting that localized stress concentrations can be significant during peak thermal events, as also reported by Collins et al. (2018) for the case of Twain Harte dam. These observations highlight that the thermal stress, though low in some contexts, may intermittently reach levels sufficient to drive crack propagation.

Regrettably, the literature on deformation ratios in thermo-mechanical contexts remains limited, complicating cross-study comparisons. Notably, the highest temperatures observed in this research corresponded to the largest deformation ratio, suggesting a potential dependency on the magnitude of thermal stress. Reporting these values contributes to building a collective dataset, facilitating a better understanding of whether deformation ratios are primarily rock-climate

dependent or exhibit consistent patterns across cases. Expanding this dataset could significantly enhance the interpretation of deformation ratios in the context of thermo-mechanical fatigue.

3. Calibration of a three-dimensional finite-difference model to the measured data, coupling thermal and mechanical solutions, in terms of displacements and stresses for the case of the Valley of the Kings.

A transient model was developed to simulate the displacements of the rock mass at both sites using Itasca's FLAC® and FLAC3D® applications. The initial approach involved constructing a two-dimensional model for each case, with dynamic thermal boundaries represented as lines fluctuating over time in both magnitude and extent. The initial trials were conducted elastically with plastic joints.

For the Långören Island case, the modelling aimed to replicate the cracking events recorded in 2014 and 2018, driven by fluctuations in rock surface temperature. Since the site was instrumented in 2016, thermal inputs were sourced from various weather stations around the island and subsequently validated with recent on-site measurements. Mapping new fractures at the rock surface assisted in validating the results by elucidating the extent of the horizontal slabs. The modelling results indicated a crack aperture to rock temperature ratio of 0.05 mm/°C, which aligns closely with the measured value of 0.04 mm/°C. Simulations corresponded to the measured crack aperture with an R^2 of 0.85.

The model for the Valley of the Kings was constructed to replicate the lateral fracture displacements recorded at the rock slabs from April 2018, when the monitoring system was installed. The incorporation of joints as explicit features in the model facilitated an understanding of both the mechanical behaviour and the necessary thermal contrasts to achieve similar temperatures and displacements. Tests revealed that thermal conductivity for intact rock can be up to three orders of magnitude higher than for joints used to model discontinuities, as also reported in other jointed scenarios by Marmoni et al. (2020). Mechanical anisotropies were tested as reported from laboratory tests for the elastic case, demonstrating that isotropic scenarios better aligned with measured fracture openings. The simulated fracture opening value correlated with measured data with an R^2 of 0.8, distinguishing between elastic and inelastic displacements. The ratio between fracture opening and rock surface temperature was 0.05 mm/°C for the measured data and 0.03 mm/°C for the simulation.

A three-dimensional model was developed for the Valley of the Kings in FLAC3D®, based on a scanned topography of the area. The selected mesh comprised 3.5×10^6 zones and was modelled

mechanically to test the model's behaviour and inputs. Sensitivity analysis was conducted to define the properties for both elastic and Hoek-Brown plastic scenarios, including the modelling of joints as plastic in all instances. Thermal analysis was performed to test the extension of thermal boundaries, which were inputted as surfaces covering the entire topography to avoid thermal anomalies. The thermal results matched the measured temperatures with an R^2 above 0.9 for various surveyed points.

A coupled thermo-mechanical solution was implemented to align the fracture opening values with measured data, using an elastic rock mass and plastic joints. The complex geometry, interface roles, and dynamic thermal boundaries necessitated iterative calibration to understand the model's behaviour over a 12-month simulation. The final outcomes indicated that the thermal expansion coefficient, the presence and properties of joints (such as stiffness and strength), and the thermal contrast between rock and joints guided the fracture opening time-series in terms of peaks, troughs, and magnitude. The results correlated with measured data with an R^2 of 0.89.

4. Introducing and discussing the fracture growth modelling approach for inelastic displacements measured in the Valley of the Kings, involving the applicability of Goodman's diagram (1899) to predict failure resulting from thermo-mechanical fatigue.

The modelling of inelastic displacements was performed through a series of tests that led to the incorporation of plasticity in specific features. Extending the simulated period to cover the entire interval from April 2018 to July 2023 revealed the inelastic displacements reported in the simulation results. Initially, plasticity was incorporated implicitly by reducing the stiffness of joints due to observed shear and normal stress accumulation in Joint 1. However, this approach was deemed geotechnically unfeasible as it risked joint failure. An alternative strategy involved reducing the Geological Strength Index (GSI) of the rock mass, which exposed deviatoric stress accumulation in Slab 1, suggesting potential crack growth. Volumetric strain remained constant, indicating that incorporating dilation into the strength parameters could better capture volumetric changes.

The most critical features for incorporating explicit plasticity were tested through the excavation of the notch section under Slab 1, known as Notch 1. This led to increased stress distribution towards the lateral fracture and the upper part of Slab 1, enhancing the deviatoric stress in these areas. Explicit plasticity was then applied at Notch 1, resulting in larger fracture openings that aligned more closely with the measured data compared to other simulations. However, the simulated trend did not exhibit the same increase over time as observed in the measured data. Additional analysis

indicated that shear stress accumulation in Joint 1 could lead to failure, prompting a final trial with reduced joint cohesion. The results suggested that a comprehensive study of joint strength inputs (cohesion, friction, tension) and their evolution with fluctuations in shear and normal stress could better match the measured data. Other strategies, such as employing a strain-softening constitutive model, incorporating frictional strength when cohesion is reduced in joints, or studying changes in thermal properties with crack evolution, are qualitatively suggested.

The final simulation reported an average fracture opening rate of 0.83 mm/year, which is lower than the measured rate of 1.06 mm/year, encompassing both elastic and inelastic displacements. Deviatoric stress calculations were presented as time-series data using Goodman's diagram. Alternating and midrange stresses were computed for each annual period, with the sixth-year period excluded due to incomplete data. The diagram effectively illustrated the transition between current and past stress states caused by thermal fluctuations and predicted potential conditions under which Notch 1 could reach failure. Failure is anticipated when the ratio of deviatoric stress to the crack initiation threshold meets the yielding criteria.

This analytical approach evaluates the impact of sustained perturbations, such as temperature fluctuations, on whether the rock mass generates elastic displacements. By analyzing various combinations of alternating and midrange stress, it is possible to determine if the deviatoric stress, at a midrange of 0, can increase up to a limit defined by the crack initiation value and thus behave elastically. Conversely, any midrange stress must remain below the crack initiation value to prevent the generation of new cracks. This method aids in predicting future scenarios and understanding the mechanical and thermal contributions to the fracturing of jointed rock masses.

9.2 Novel Contributions

This dissertation examined the thermally assisted fracturing of ancient rock surfaces due to environmental effects at two sites with distinct geological and environmental conditions. The research on Långören Island is notable for its documentation of spontaneous and active thermal fracturing processes, which are rarely captured in existing studies and offer significant insights to the scientific community. Conversely, the Valley of the Kings, a UNESCO World Heritage site, underscores the importance of the study for preservation efforts. Additionally, it introduces a substantial dataset of mechanical and thermal measurements, with ongoing monitoring up to the date of this thesis publication. The novel contributions of the research include:

1. A detailed review of global thermo-mechanical site investigations, encompassing measured data, conceptual models, and numerical simulations.

2. A comprehensive rock mechanical laboratory program for samples collected from the Valley of the Kings, featuring the first strain-stress analysis and publication of crack initiation thresholds in Egypt.
3. Characterization of the weather conditions at the Valley of the Kings, with data collected from above tomb KV42.
4. A proof of concept for thermo-mechanical cycles, integrating measured and simulated data to report ratios between fracture opening and rock surface temperature, as well as rates of opening in mm/year. This study is the first in Egypt to focus solely on thermal fluctuations, without water impact, as the driving agent for displacements.
5. Development of a thermo-mechanical transient model in FLAC3D® with dynamic boundary conditions, allowing for the incorporation of thermal functions to more accurately represent rock temperature fluctuations and solar patterns.
6. Application of Goodman's diagram (1899) to illustrate thermo-mechanical fatigue, capturing the transitions between cycles using a dynamic approach and setting a failure criterion based on crack initiation thresholds. This approach could be tested in other scenarios.

9.3 Limitations of Research and Future Work

From the inception of this research, we have worked to address and mitigate limitations to minimize their impact on our analysis. This included defining a framework specifically focused on thermo-mechanical fatigue, enhancing the monitoring system's capabilities, and refining the numerical modelling outcomes. While the discussion of results is centered on current findings and theoretical interpretations of potential outcomes, these could be significantly expanded through future research in these areas. Therefore, a detailed outline of current limitations and directions for future work is provided to facilitate the continued exploration of these concepts in the Valley of the Kings.

9.3.1 Thermo-mechanical Fatigue and Weathering of Rocks

Through the development of this research a common misleading question from both technical reviewers and non-specialist in the engineering geology field involved the differentiation between thermo-mechanical fatigue from weathering and erosion in rocks. Despite of origin, location and indicators are different in reality these two processes are interconnected without a clear precedence. Hence, the importance of isolating different potential triggering agents to thermo-mechanical fatigue.

A clear distinction between thermo-mechanical fatigue and weathering can be made by comparing the findings of this research with the key concepts of weathering. Thermo-mechanical fatigue is primarily driven by thermal stress cycles and is typically studied from a geotechnical perspective. In contrast, weathering results from chemical, physical, and biological processes, that may or may not involve temperature variations in cyclic or increasing conditions. Thermo-mechanical fatigue generally affects the surface or near-surface rock around heat sources, occurring relatively quickly in response to thermal cycling. Conversely, weathering can impact rock at any depth and is usually a slow, long-term process, influenced by the nature and exposure to weathering agents. Locations prone to thermo-mechanical fatigue can be identified by observing surface spalling, cyclic fracture openings, crack patterns, and heat-affected zones, which can be measured through thermal interaction and stress response. In contrast, signs of weathering include discolouration, mineralogical changes, increased porosity, and erosion, often resulting in soil or regolith formation and are typically studied with a focus on mineralogical changes and mineral composition.

The Valley of the Kings presents a unique opportunity to study thermo-mechanical fatigue in an environment where chemical and biological weathering plays a less dominant role than in other locations worldwide. While weathering from chemical and biological processes does occur in the area, its impact on shaping the landscape over engineering timescales (centuries) is minimal compared to its influence over geological timescales (thousands of years). However, it remains essential to conduct a microscopic study of the mineralogical composition of the micritic limestone and to evaluate the rates of transformation under weathering processes. This assessment will help determine whether the current environmental conditions are significantly contributing through weathering to the displacement of the rock column.

9.3.2 Fieldwork and Monitoring

Site visits have primarily aimed to maintain and improve the monitoring system, although mapping new cracks or conditions in the rock mass was conducted in parallel. These visits, approved by the Egyptian Government, were limited in time due to site restrictions and the requirement to work under the supervision of Egyptian inspectors for a specified number of hours each day. Therefore, priority was given to ensuring the monitoring system functioned properly, with time allocated afterwards for mapping and characterizing the rock mass.

Visual documentation of the site, including the overall surroundings of the Valley of the Kings, was essential for assembling and corroborating the on-site mapping. However, this approach was not always ideal, and some relevant details may have been overlooked or only prioritized after analyzing new research findings. For example, after reviewing the 3D simulation results, it became

apparent that the mapping of joints was limited to the characterization of the most exposed edges on the eastern side (accessible area). The western side was described hypothetically, as the joint surface conditions were assumed to be regular, with joint openings allowing visualization of the western end, at least for Joint 1. The stiffness properties of the three joints were assumed to be equivalent, based on a Schmidt hammer rebound test on loose rock blocks and the mapping evidence. This assumption limits the range of properties and raises questions about the actual differences between the three joints.

Regarding direct shear tests conducted on the joints, the area is subject to local public policies and UNESCO restrictions, making sample extraction a challenging task. Additionally, drilling across the joints could alter the landscape and raise concerns about the stability of the rock column during the operation. Therefore, directly testing the properties of the joints may not be feasible, but less invasive techniques can be used to map other characteristics of the joints. For instance, the presence of open planes or rock bridges between joint planes can be studied using ground-penetrating radar and ultrasonic testing. This would allow for a revised definition of the joints, increasing the tensile bonding limit if rock bridges exist between them, or even limiting the extension of joints if the planes are not continuous at depth or towards the western side.

Improvements to the integrated monitoring system primarily involved deploying new sensors in the rock column. While technically straightforward, this posed a diplomatic challenge due to the complexities of obtaining work permissions at the site. Consequently, relying solely on the existing sensors significantly limited the interpretation of data and the calibration of models. For example, the current setup includes only one sensor to record opening displacement, oriented along the East-West axis. This configuration fails to capture the normal movement of the rock column in the North-South direction, thereby missing the opening of Joint 1. A comprehensive vector measurement incorporating both shear and normal displacements would have allowed for more accurate calibration of the overall movement of Slab 1 using modelling data, thereby enhancing the validation of the model. Furthermore, it would have provided actual values to determine the joint properties on a rock mass scale by measuring the normal and shear displacements at one end of the joint. Additional sensors should ideally be placed to measure temperatures at various strategic locations, such as across Slab 1, the notch area, and the lateral fracture. A second thermal camera, oriented towards the North-South section, would also be beneficial to capture the thermal contrast between joints. This contrast is currently only represented through numerical calibration.

9.3.3 Modelling of Inelastic Displacements

Major limitations were faced during the 3D modelling construction, particularly at the mesh creation with such a large number of elements. The mesh was refined to a scale of centimeters to accurately represent the relevant features, particularly the lateral fracture and joints. However, this arose the warning that computational capacity needed to be expanded, which took months to be determined since the model is a self-programmed code. Despite the availability of new resources, the model coding required further optimisation to reduce computational time, which ultimately ranged from 2.5 to 3.5 hours per simulated month (longer during colder periods), based on the thermal total time for thermo-mechanical simulations. Future work should be focused on reducing the computational time, by limiting the calculation area or incorporating fixed boundary conditions that speeds up the calculation process. The mesh could also be improved by coarse-graining the elements at the bottom; however, a transition layer to the rock column is needed to ensure the smoothing of the geometry. These would contribute to minimize the waiting time and increase the simulation scenarios to test more parameters and conditions.

This study details the model's behaviour, including recommended inputs for the initial 12 months and other strategies to align the inelastic displacements throughout the simulation period. However, the modelling of joints indicates that additional iterations are necessary to accurately determine the appropriate inputs for joint behaviour. Specifically, the interaction between strength parameters, such as cohesion, friction, and tension; it could result in irreversible fracture opening of Slab 1 without requiring plastic settings within the column zones, potentially reflecting the implicit plasticity of the rock mass.

Overall, a refinement of the thermo-mechanical properties is essential for accurately understanding the contrast between the thermal behaviour of intact rock and joints. While intact rock properties are commonly used in thermo-mechanical models, a parameter to represent the thermal conductivity of the entire rock mass, including joints, is necessary for more precise calibration. In this research, two distinct thermal regions were defined, though not directly inputted into the three-dimensional model, as the model was not capable to explicitly incorporate thermal properties of joints. This omission underscores a broader issue in rock mechanics modelling, where differentiating between the thermal properties of rock and joints is often neglected, despite its critical importance.

The mechanical properties of joints, which are frequently mentioned in this dissertation, are also crucial inputs for future investigation. Sensitivity analysis, in particular, will be essential for calibrating the model and understanding the interactions among the three main joints. Both the

thermal and mechanical properties of the joints were modelled within a narrow range of values, but this range could be expanded through additional case simulations to better capture the variability observed in real-world scenarios.

After completing the long-term calibration of joint parameters over the period from 2018 to 2023, further analysis focusing on the plasticity settings of the rock mass could be undertaken. This would help in assessing potential fracturing at key structural elements, such as Slab 1, Notch 1, and the Lateral Fracture, offering a more comprehensive understanding of the rock mass behaviour under thermo-mechanical loading.

To explicitly model inelastic displacements, alternative constitutive models that allow for changes in strength limits during deformation could be considered. For instance, the strain softening-hardening approach for brittle rocks, although challenging to implement, could be replaced by a simplified cohesion-weakening-friction-strengthening (CWFS) model to better align simulated data with observations. Time-dependent models for fracture opening could also be an option to more accurately predict fracture progression, but they pose a challenge in parameter determination, particularly under creep behaviour conditions.

Modelling inelastic displacements can be approached using numerous strategies, including the consideration of factors not measured or explored in this research. While this work focused on damage accumulation and subsequent fracture propagation from a thermo-mechanical fatigue perspective, other factors could also play a role in defining strength limits. For example, a microscopic study of rock samples and an analysis of changing environmental parameters could provide a dynamic understanding of rock properties. Although these aspects were beyond the scope of this research, they are recommended for future study to enhance the understanding of rock behaviour under thermo-mechanical fatigue.

9.3.4 Data Analysis and Safety Protocols

The rock column at the Valley of the Kings is located near pedestrian paths and above the entrance of tomb KV42, which highlights the necessity of establishing safety protocols to mitigate potential risks associated with its stability. However, the precise determination of when and how to prevent such risks remains contentious given the current data limitations.

Recent measurements of fracture opening have shown positive trends that are hypothesized to be linked to inelastic displacements, possibly due to the extension of the lateral fracture. Yet, there have been no macroscopically detectable new signs of cracking on the front face of the rock mass, as gypsum marks from 2017 remain intact. This raises a critical question: do these apparent

inelastic displacements represent larger, permanent displacements that will not return to their original state, or is the current trend part of a larger cyclical pattern that will eventually see the fracture opening reduce to zero over time? If the latter scenario holds, it would suggest that the lateral fracture remains structurally sound despite the thermo-mechanical cycles, and the fatigue limits of the rock mass have not yet been reached under present conditions. This hypothesis would align with a constant difference between the fracture's minimum and maximum opening values, which could be expected to widen over time.

On the other hand, if continuous fracturing is occurring, albeit not visibly on the front face, it could signal the need for an early warning system to alert officials about the risk of the column's collapse, should protective measures not be implemented. This approach would involve a detailed analysis of fracture opening rates, with special attention to accelerations in deformation that could indicate abnormal movement trends. By monitoring such trends, officials could detect early warning signs of instability.

The implementation of a comprehensive monitoring system would require defining protective stages that prevent catastrophic scenarios. One of the first measures would be to establish a safety zone, restricting the proximity of tourists to the column and outlining protocols for personnel working within the risk area. This zone should be determined based on the potential radius of impact should the column fall.

Additionally, protecting the entrance to tomb KV42 would be essential. A robust surface should be constructed to cap the steps leading to the tomb's portal, preventing debris from reaching it in the event of a rockfall. Moreover, as previously mentioned, constructing a protective wall could reduce the temperature contrast between the notch and slab sections of the column, thereby minimizing thermal stress fluctuations and promoting the stability of the rock mass. Continuous monitoring systems, equipped with accelerometers and inclinometers, could provide real-time data on the overall stability of the structure. These systems, connected online, would allow for remote monitoring, contingent on securing reliable power and connectivity for the sensors. Such an approach would provide critical data for ongoing safety assessments and ensure timely responses to any signs of instability.

While the above measures focus on non-invasive strategies, typical rock mass improvements, such as grouting or reinforcement, or even the removal of unstable slabs, could be considered in such situations. However, given the site's designation as a cultural heritage location, these interventions are highly unlikely to be implemented due to their potential impact on the site's

authenticity and historical value. Instead, efforts are concentrated on preservation strategies that align with heritage conservation principles.

This research has provided an initial insight into the stability of the rock column at the Valley of the Kings, highlighting critical considerations for monitoring and safety protocols. While the findings offer a foundation for understanding the current conditions and potential risks, further studies could enhance the accuracy of predictive models and inform more effective stabilization measures. Such approaches, combining detailed monitoring, protective structures, and thermal regulation strategies, could be applied to other sites within the Theban Necropolis or similar rock-cut ancient monuments worldwide. By mitigating the risk of structural degradation, these efforts would not only preserve these invaluable cultural and historical landmarks for future study but also ensure their continued enjoyment by generations to come.

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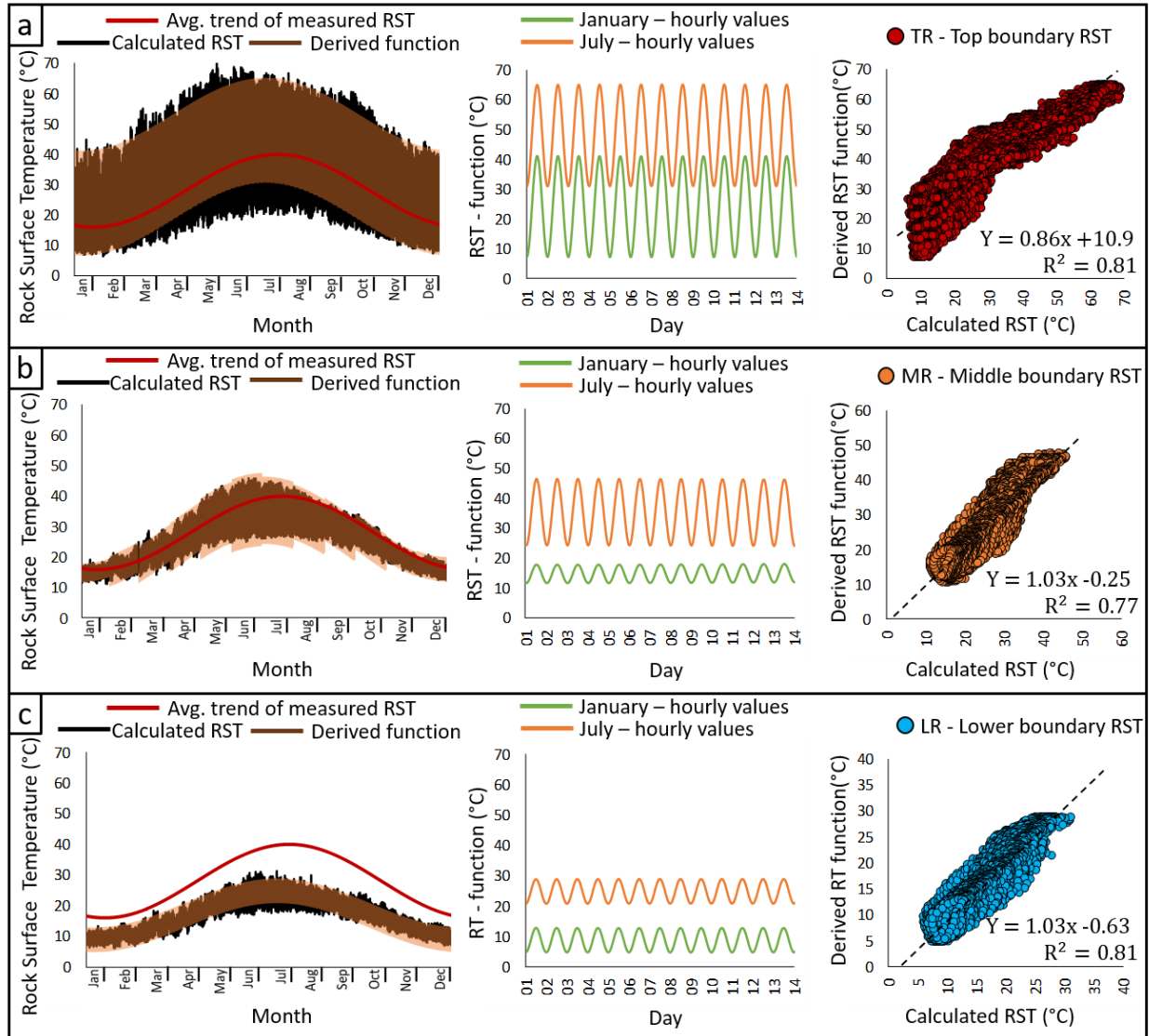
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APPENDIX A

	Initial	After 2 nd cycle	Retained		Initial	After 2 nd cycle	Retained
Marly limestone			Big rounded-edgeless polished pieces, with smaller one-axis extended fragments. Small cracks are seen in bigger pieces. Smaller fragments did not pass due to shape-wise.	Micritic limestone			Big very-rounded polished pieces, cracks are seen in bigger pieces. Very few small fragments were retained.
			Big rounded-edgeless polished pieces, cracks are seen in bigger pieces. Cavities and fine material on surface of pieces, possibly due to expansive clay effects.				Big very-rounded polished pieces, cracks are seen in bigger pieces. Cavities and small cracks on surface of pieces, possibly due to expansive clay effects.
			Big rounded polished pieces, cracks are seen in bigger pieces. Cavities and fine material on surface of pieces, possibly due to expansive clay effects.				Big rounded-edgeless polished pieces, with smaller sheet-like rounded fragments. Smaller fragments did not pass due to shape-wise.
			Big rounded polished pieces. Cavities and cracks on surface of pieces, possibly due to expansive clay effects.				
			Small rounded rough pieces. Cavities and cracks on surface of pieces, possibly due to expansive clay effects. Around 50% of mass is due to small fragments (bagged), which had a sheet-like rounded shape.				

Appendix A - 1: Slake durability tests. Original tested subsamples and retained fragments after the second cycle of slaking. Description of retained fragments have been added along with differentiation by blocks and lithology. There were no differences in colour between samples, though pictures were taken at different light intensities.

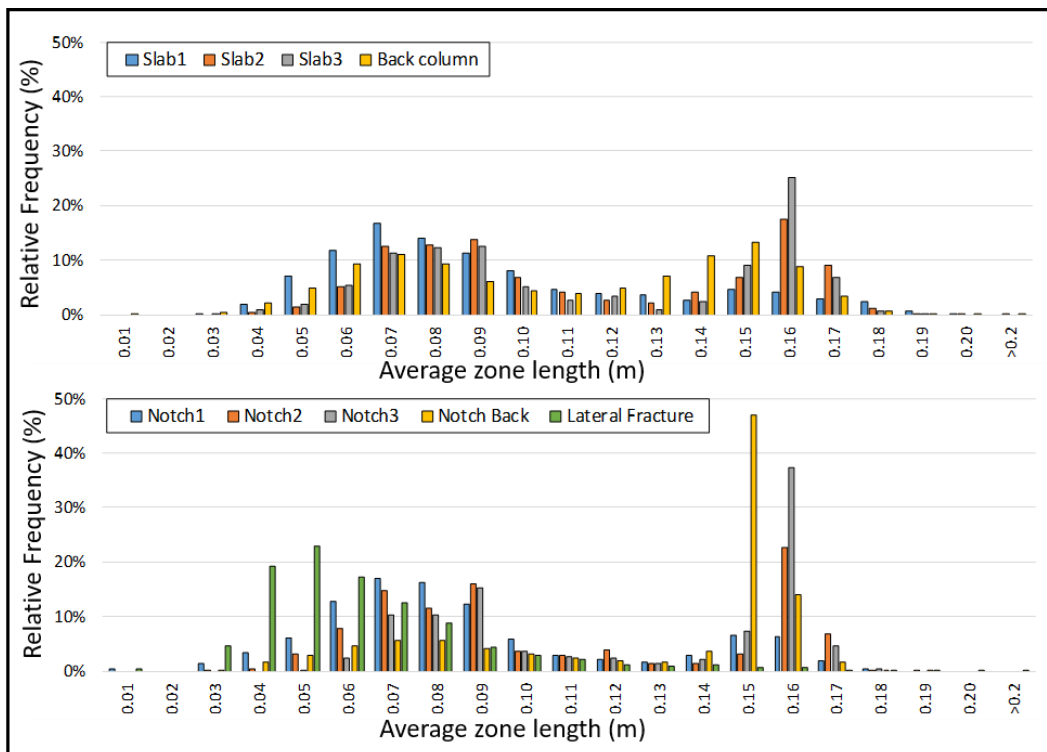
APPENDIX B



Appendix B - 1: Thermal boundary derived function, coupling monthly and daily variations. The rock surface temperature was calculated with Bentz (2000) model, using local weather data. The boundary function time-series plot shows the average trend of measured rock surface temperature, along with the calculated and derived function. Derived hourly values for January and July are displayed to show expected fluctuations within a day. Scatter plots of derived rock surface temperature function values and calculated rock temperatures are displayed, including the correlation factor R^2 between both time-series for a) top boundary, b) middle boundary and c) lower boundary. Location of boundaries is presented in Figure 5-6 and Figure 5-9.

APPENDIX C

The characterization of zone size per region is expressed in terms of the mean length of all faces within each zone. These measurements are depicted in histograms, specifically focusing on lengths below 20 cm within the identified regions of interest along the rock column. For Slab 1, approximately 71% of zones exhibit lengths shorter than 10 cm, while for Slab 3, this proportion decreases to only 50%. Slab 2 and the column section situated behind Joint 3 (referred to as the "Back Column" behind Slab 3) display data clustering around two distinct values, notably 7 cm and 16 cm. This trend is similarly observed in the regions of the slab beneath the notch section. Conversely, the notch area behind Joint 3, referred to as the "Notch Back," demonstrates a pronounced concentration around a length of 15 cm for zone lengths. Notably, the zones associated with the Lateral Fracture exhibit the shortest average length, measuring only 6 cm. This characteristic is primarily attributed to the small geometry and the positioning of this cluster of zones.



Appendix C - 1: Histogram of zones sizes per group.

Geometrical considerations in terms of zone shape were taken into account once the geometry was imported in FLAC3D®. The geometry quality assessment considered both the volume relative to a characteristic length (Quality-1) and the degree of distortion by comparing ratios of edges to faces and orthogonality of zones (Orthogonal) across all internal faces of a zone, throughout the

use of FLAC3D® commands. (Itasca Consulting group, 2019). The extracted parameters are introduced in Appendix C - 2. Although the concept of quality may be specific to the objectives and geometry of the study case, available literature may deliver a criterion for mesh performance which helps in reducing the significant time to build complex geometries. Specifically, studies on high-quality mesh generation in FLAC3D® have concluded that Quality-1 and orthogonality indices above 0.5 typically limit the relative error to 5% and include at least 50% of the entire zone population (Abbas et al. 2013, Wang et al. 2020).

Appendix C - 2: Zone quality data extracted from FLAC3D®. Quality-1 refers to the ratio volume to edge length (values closer to 1 indicates low mesh distortion), whereas orthogonal indicates the orthogonality of the zone (value = 1 fully orthogonal).

Variable	Parameter	Slab 1	Slab 2	Slab 3	Notch 1	Notch 2	Notch 3	Lateral Fracture
Quality-1	Average	0.53	0.59	0.60	0.56	0.59	0.64	0.48
	Std. Dev.	0.17	0.15	0.14	0.17	0.15	0.12	0.18
	Quartile (25%)	0.41	0.49	0.51	0.44	0.49	0.56	0.35
	Quartile (75%)	0.66	0.69	0.70	0.68	0.70	0.72	0.61
Orthogonal	Average	0.66	0.76	0.77	0.67	0.74	0.82	0.56
	Std. Dev.	0.22	0.20	0.21	0.21	0.22	0.19	0.23
	Quartile (25%)	0.49	0.61	0.62	0.52	0.58	0.68	0.39
	Quartile (75%)	0.86	0.96	0.97	0.85	0.95	0.98	0.74

APPENDIX D

; The following script details the commands to set the mechanical conditions for the geometry of the ; rock column above the tomb KV42 in the Valley of the Kings.

; FLAC34 V7.00.157

; Rodrigo Alcaino-Olivares & Matthew A. Perras

; Developed in 2022 – 2024

; Create a new model, disable large-strain effects and automatic creation of entities

model new

model large-strain off

fish automatic-create off

model deterministic off

; Specify a log file to record console's output

log-file '000LOGS\Mechanical.log'

log on

; Configure the model for mechanical and thermal analysis

; Note: this command does not activate the type of analysis, but it is needed to configure the module

; if other modules are needed, they must be set at this point.

; There is no option to tell FLAC what modules to use later

;so it is essential to specify this at the beginning

model configure mechanical

model configure thermal

; Import the geometry in .f3grid format. This geometry has the basic groups already defined, such as ; Slab 1 or debris, for instance.

zone import 'KV42_GEOMETRY.f3grid'

; ensure that the mesh is well attached in their gridpoints and faces.

zone gridpoint merge tol-rel 0.001 tol-abs 0.0

zone attach by-face tol-rel 1.0e-5 tol-abs 0.0

zone validate

; save the model prior to any mechanical setting

model save '02BaseModel\Run00_Geometry.sav'

; Fixing mechanical boundaries and initial stress conditions

model gravity 9.81

zone gridpoint fix velocity-x range union position-x -10 position-x 10

zone gridpoint fix velocity-y range union position-y -20 position-y 10

zone gridpoint fix velocity-z range position-z -10

zone face apply stress-zz -3.4e4 servo ramp ratio local range position-z 10 group 'CLIFF' slot 1

; Assign elastic constitutive model and properties

; Note that groups are already assigned in Slot 1 for KV42_GEOMETRY.f3grid

zone cmodel assign elastic

zone property density 2000 bulk 2.26e9 shear 1.63e9 range group 'CLIFF' slot 1

(...)

zone property density 2000 bulk 2.26e9 shear 1.63e9 range group 'C6N3' slot 1

; Create extra variables to assign in plots

define extraVar

local Z

loop foreach Z zone.list

zone.extra(Z,1) = (zone.stress.min(Z) - zone.stress.max(Z)); Deviatoric Stress

zone.extra(Z,2) = zone.state(Z); zone state

zone.extra(Z,3) = math.round(zone.vol.deformed(Z)*1e5)/1e5; zone deformation

endloop

end

@extraVar

; Create histories based on zone location for two specific points (Fracture opening and lateral Fracture) and zone ID

model history name 'unbal' mech unbal-max

model history name 'ratio' mech ratio-local

zone history name 'FOXD' displacement-x position (0.192, -0.837, 5.49)

zone history name 'FOYD' displacement-y position (0.192, -0.837, 5.49)

zone history name 'FOZD' displacement-z position (0.192, -0.837, 5.49)

zone history name 'FO-unF' unbalanced-force position (0.192, -0.837, 5.49)

zone history name 'LFS1' stress position (-0.173, -0.423, 1.9246)

zone history name 'LFSR' strain-rate position (-0.173, -0.423, 1.9246)

zone history name 'LFSI' strain-increment position (-0.173, -0.423, 1.9246)

zone history name 'LF-unX' unbalanced-force-x position (-0.173, -0.423, 1.9246)

zone history name 'LF-unF' unbalanced-force position (-0.173, -0.423, 1.9246)

; Create histories for horizontal displacements in east-west orientation

zone history name '1100-DX' displacement-x zoneid 2004033

(...)

zone history name '1100-DX' displacement-x zoneid 976502

;continues to create all histories


```
; Activate mechanical configuration
model mechanical active on
model thermal active off
```

```
; Initialize displacements and initial velocities to 0
```

```
zone gridpoint initialize disp-x 0
zone gridpoint initialize disp-y 0
zone gridpoint initialize disp-z 0
zone gridpoint initialize vel-x 0
zone gridpoint initialize vel-y 0
zone gridpoint initialize vel-z 0
```

```
; solve elastic model
model solve ratio 1e-6
@extraVar
model save '02BaseModel\Run00_elastic.sav'
```

```
-----
--
```

```
; Solve for plastic constitutive model with joints
; Create joints between group of zones
```

```
zone interface 'INT1C0' create by-face separate range group 'SLAB1' slot 1 group 'SLAB2' slot 1
(...)
```

```
; ensure that the mesh is well attached after interface creation
; note: if grid points are re-attached, then interfaces are closed
; so, attachment must be only done by-face
zone attach by-face tol-rel 1.0e-5 tol-abs 0.0
zone validate
```

```
; Assign properties to interfaces
zone interface 'INT1C0' node property stiffness-shear 20.7e9 stiffness-normal 207e9 friction 35
.....dilation 30 tension 0.5 shear-bond-ratio=50
(...)
```

```
; Assign plastic properties, Hoek-Brown to rock mass
zone cmodel assign hoek-brown
zone property density 2000 bulk 2.26e9 shear 1.63e9 constant-sci 15e6 constant-mb 0.17
.....constant-s 0.0013 constant-a 0.51 range group 'CLIFF' slot 1
(...)
```

```

; Assign plastic properties, Mohr-Coulomb to debris layer
zone cmodel assign mohr-coulom range group 'DEBRIS' slot 1
zone property density 2000 bulk 0.2778e6 shear 0.2083e6 cohesion 0.2e6 friction 30 tension 0
.....dilation 10 range group 'DEBRIS' slot 1

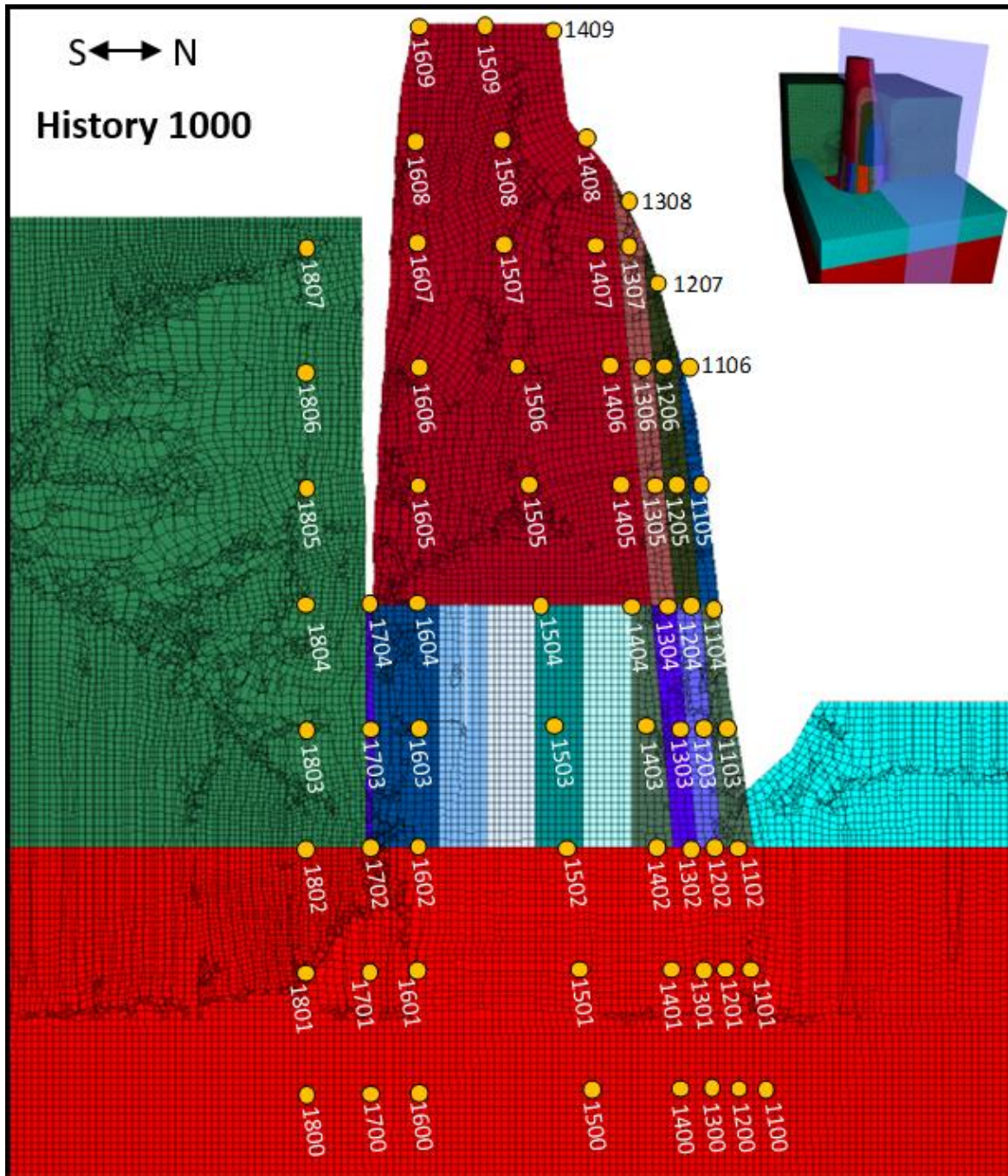
; Initialize displacements and initial velocities to 0

zone gridpoint initialize disp-x 0
zone gridpoint initialize disp-y 0
zone gridpoint initialize disp-z 0
zone gridpoint initialize vel-x 0
zone gridpoint initialize vel-y 0
zone gridpoint initialize vel-z 0

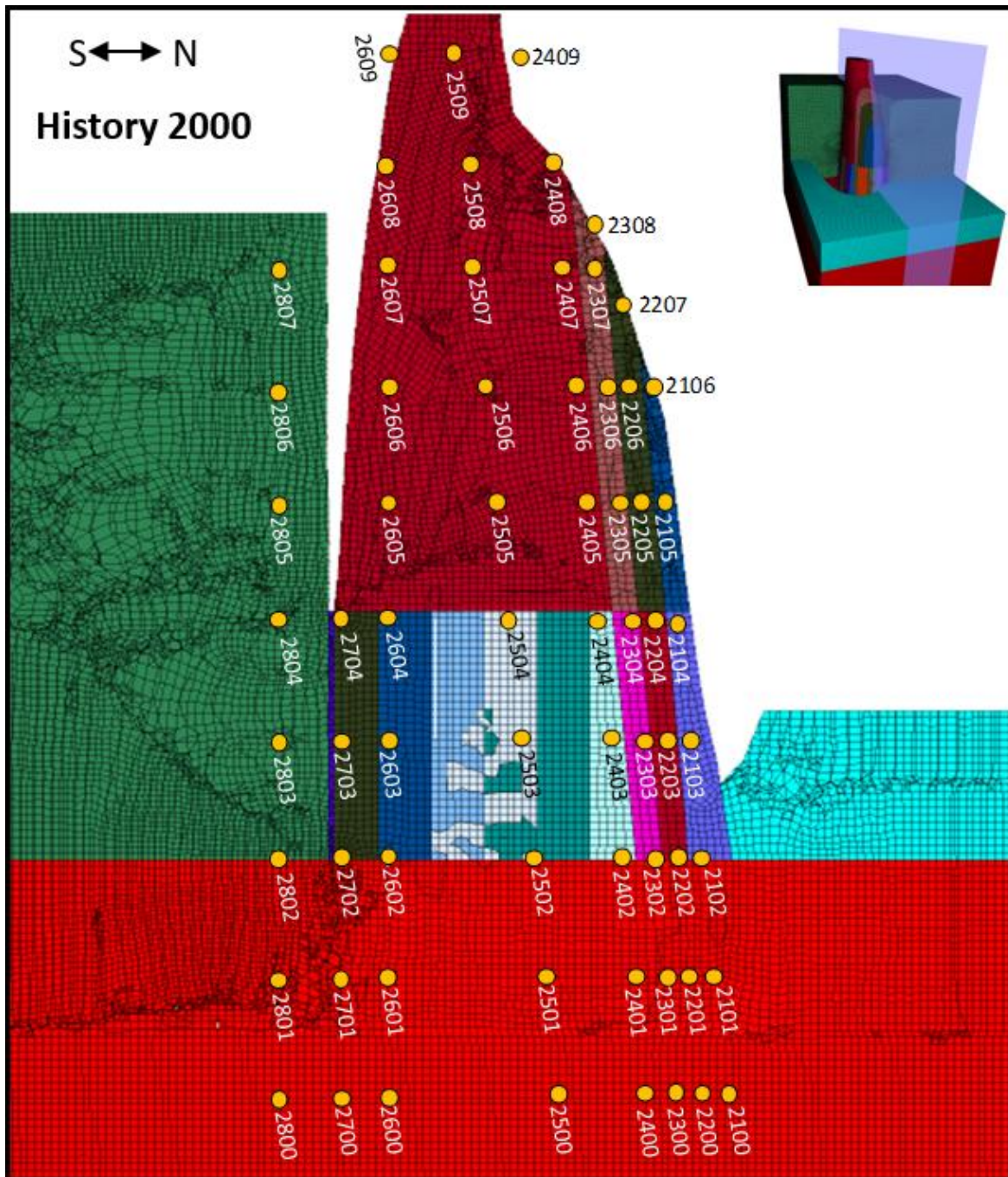
; solve plastic model
model solve ratio 1e-6
@extraVar
model save '02BaseModel\Run00_plasticWjoints.sav'

```

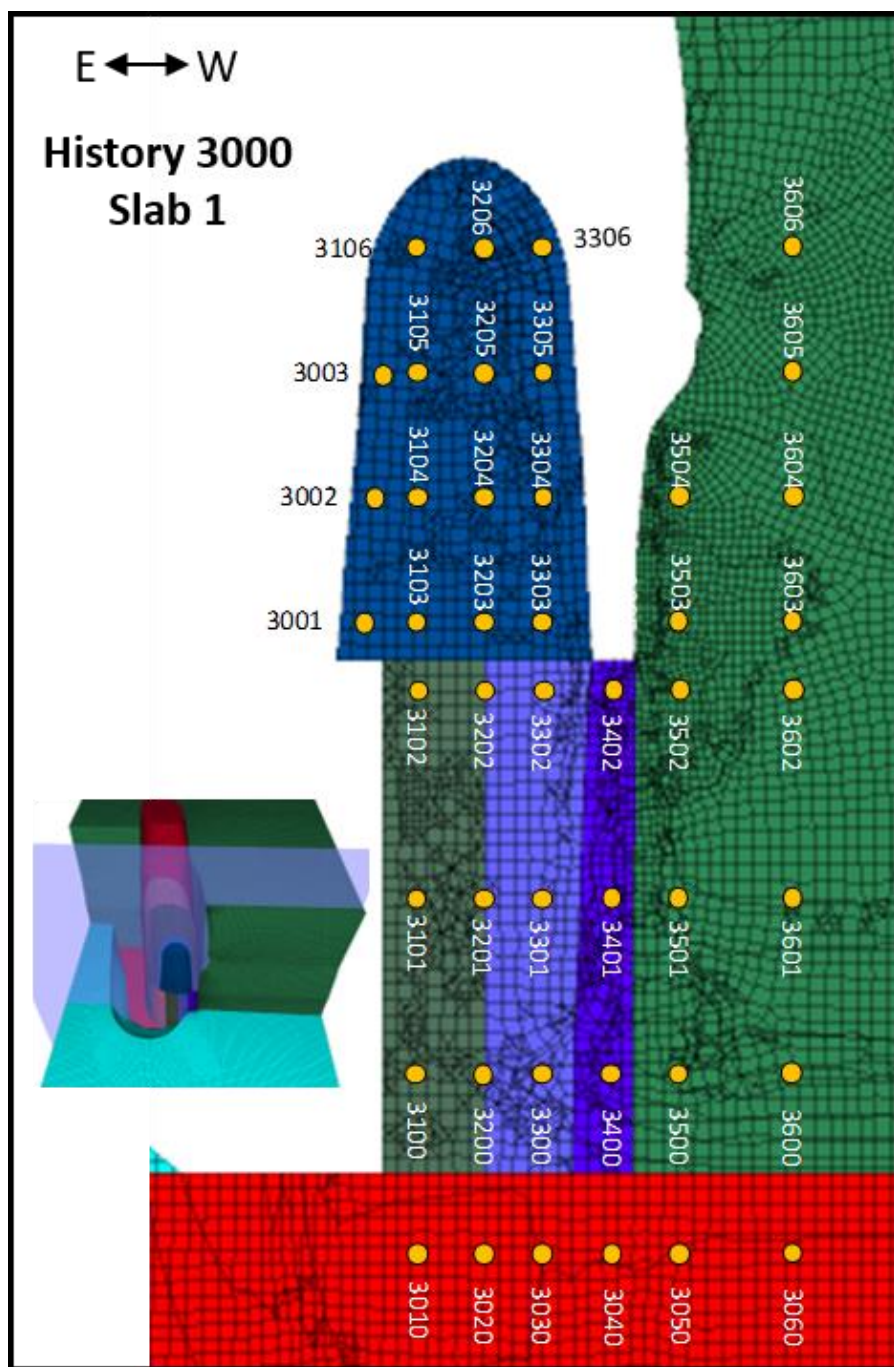
APPENDIX E



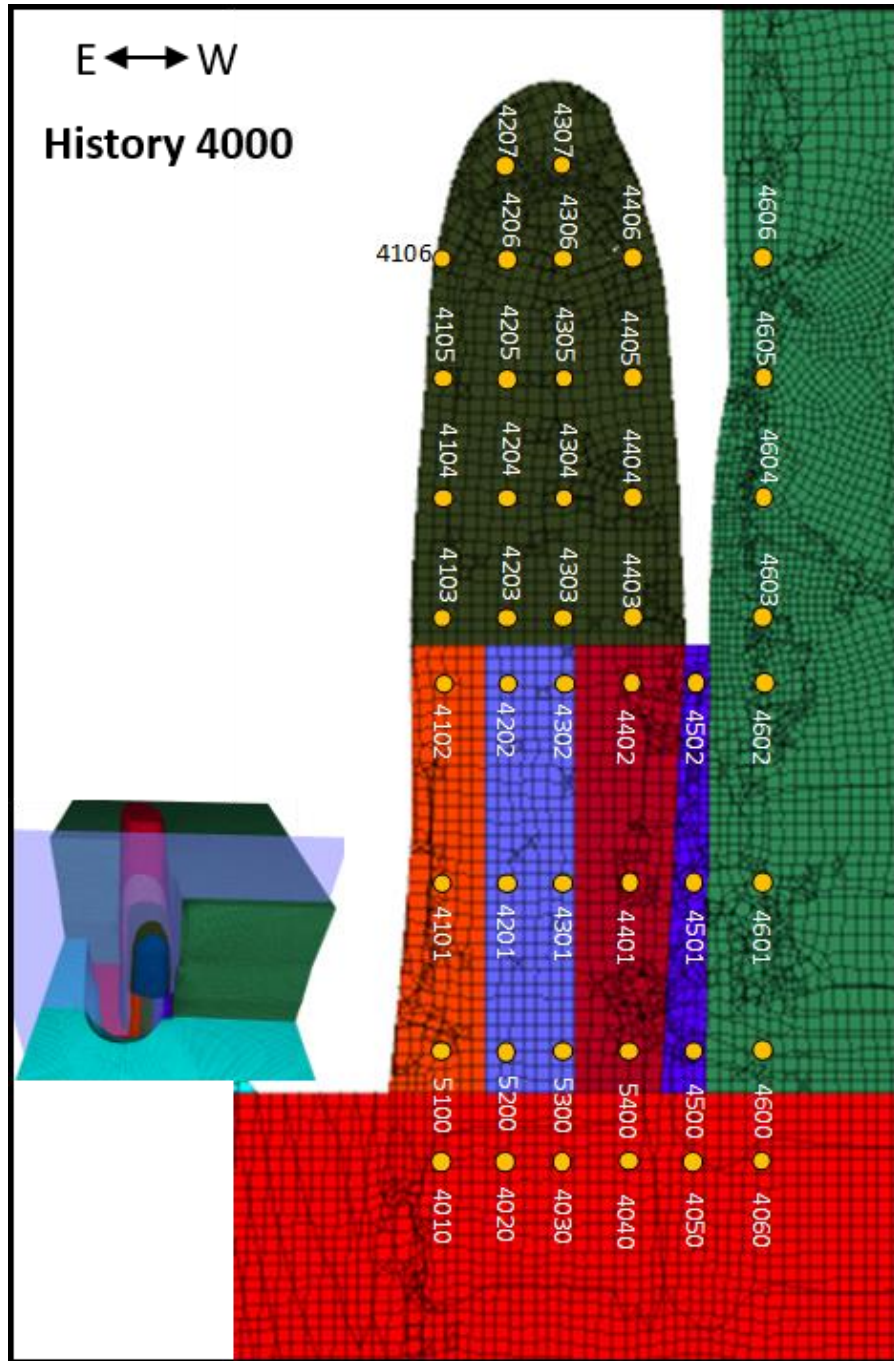
Appendix D - 1: Histories 1000. North-South cross section with the location of surveys for saving histories of data.



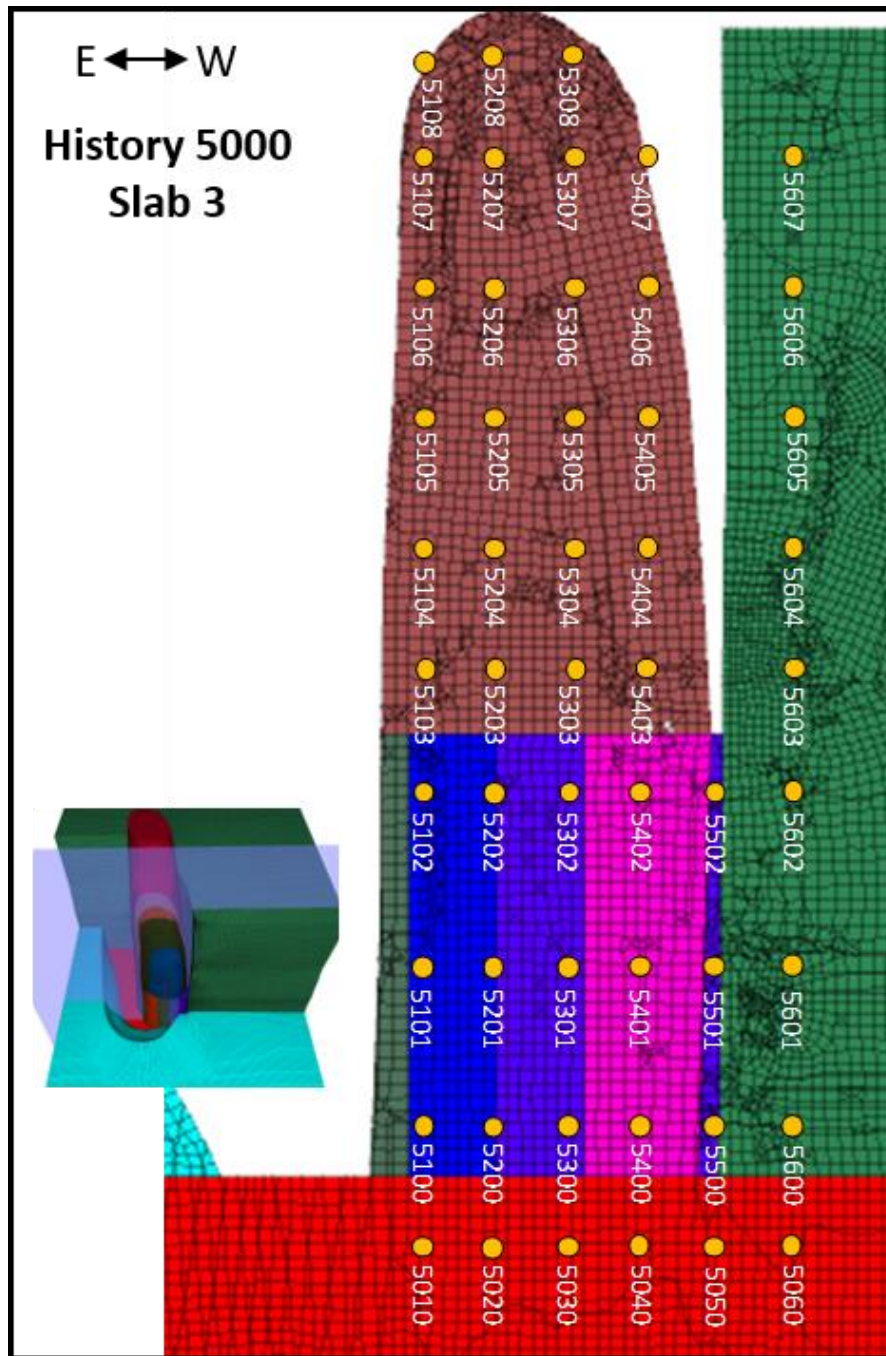
Appendix D - 2: Histories 2000. North-South cross section with the location of surveys for saving histories of data.



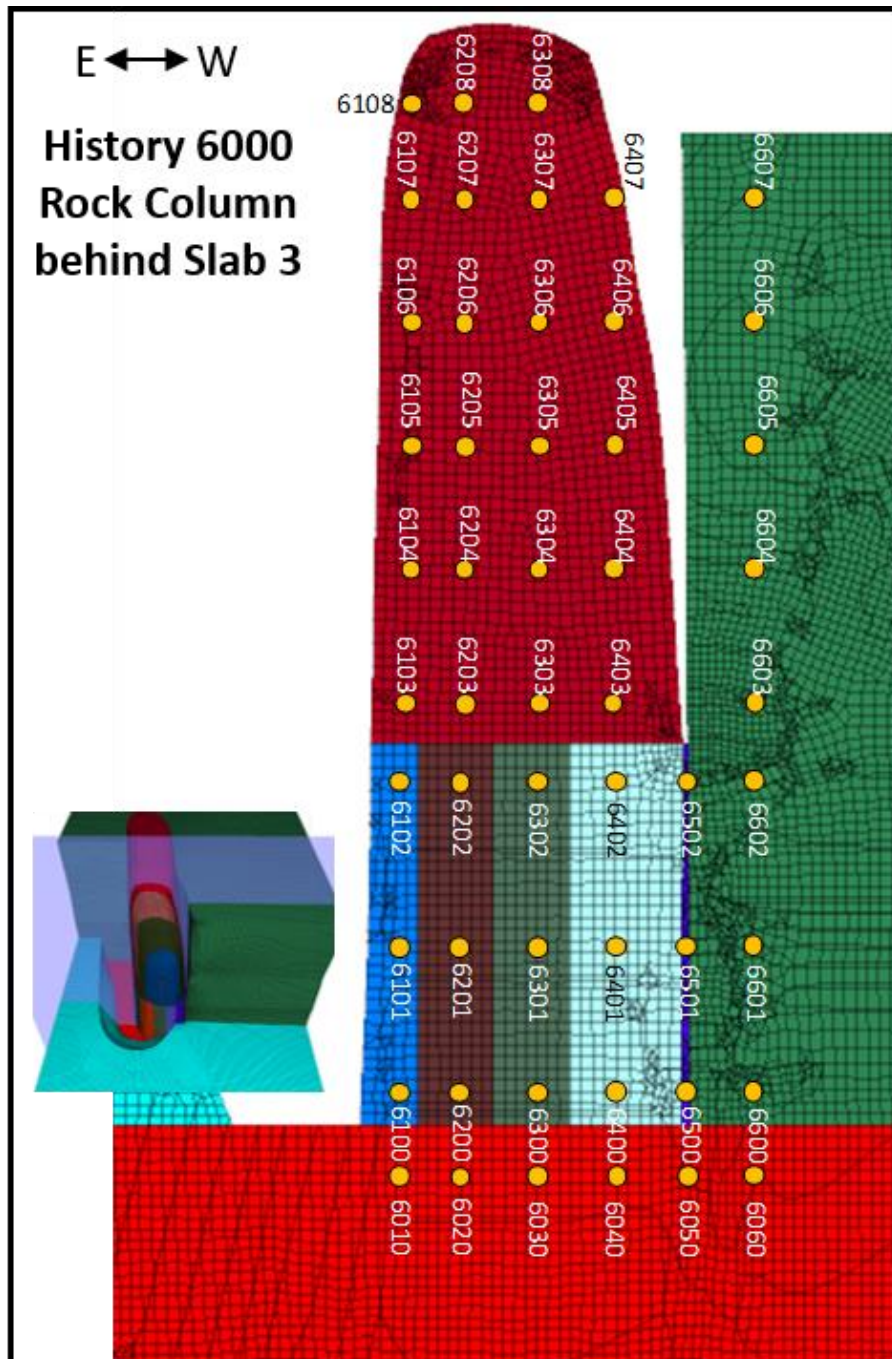
Appendix D - 3: Histories 3000. East-West cross section with the location of surveys for saving histories of data in Slab 1.



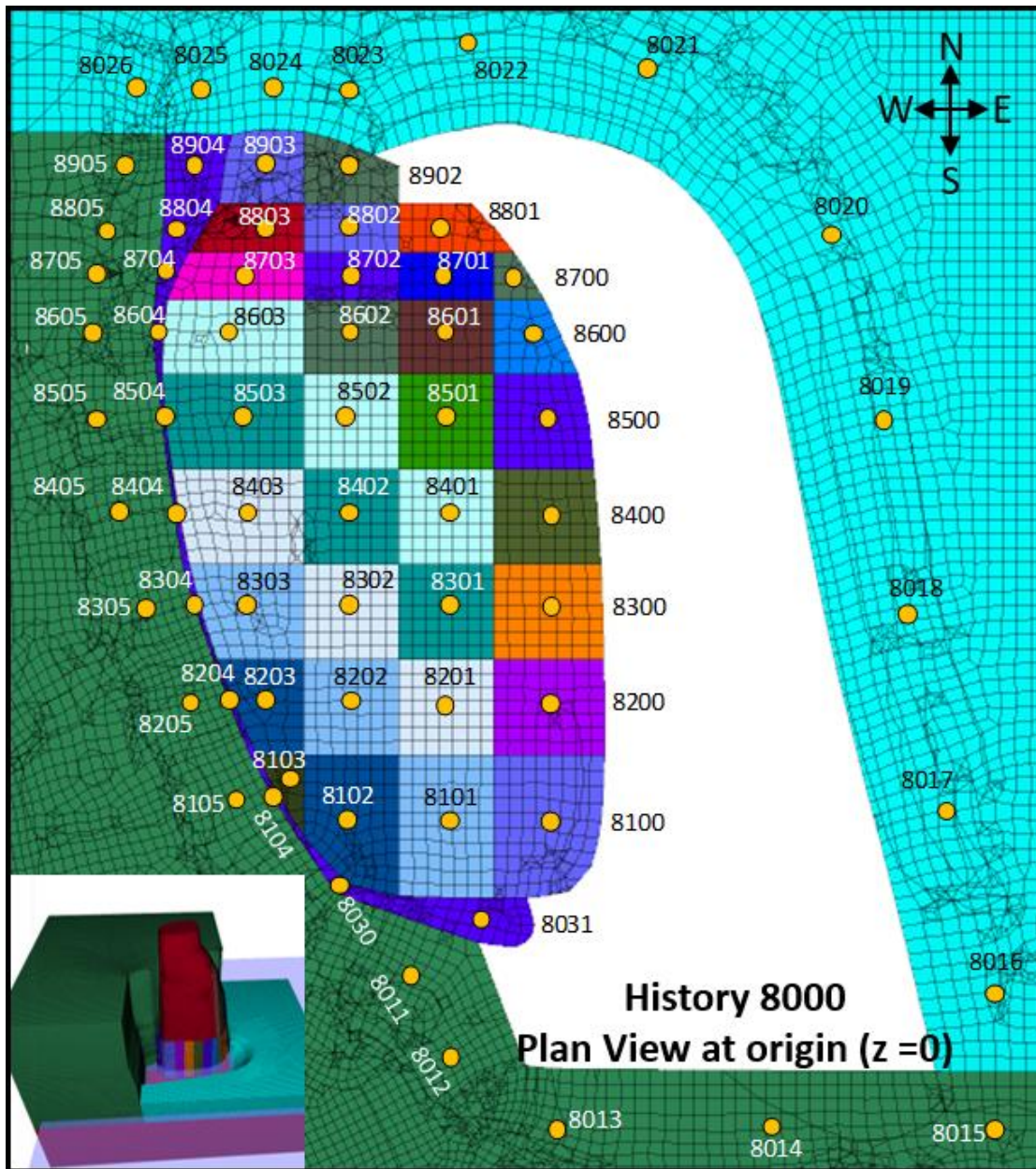
Appendix D - 4: Histories 4000. East-West cross section with the location of surveys for saving histories of data in Slab 2.



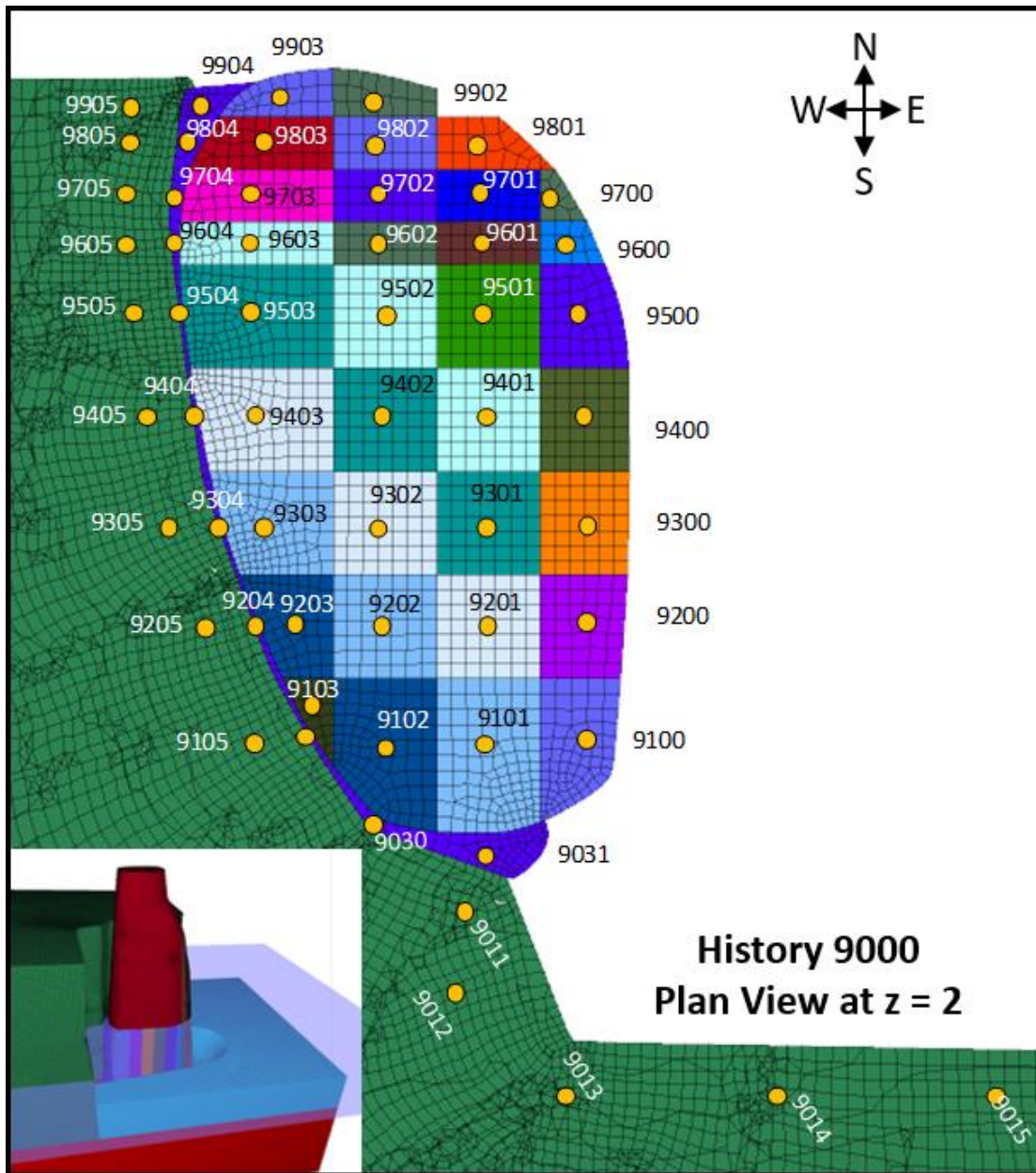
Appendix D - 5: Histories 5000. East-West cross section with the location of surveys for saving histories of data in Slab 3.



Appendix D - 6: Histories 6000. East-West cross section with the location of surveys for saving histories of data in rock column.



Appendix D - 8: Histories 8000. Plan view with the location of surveys for saving histories of data.



Appendix D - 9: Histories 9000. Plan view with the location of surveys for saving histories of data.

APPENDIX F

```
; The following script details the commands to set the thermal conditions for
; a given mechanical solution in FLAC3D
; FLAC34 V7.00.157
; Rodrigo Alcaino-Olivares & Matthew A. Perras
; Developed in 2022 – 2024

; restore model after the plastic run with joints
model restore '02BaseModel\Run00_plasticWjoints.sav'

; deactivate the mechanical configuration and activate the thermal ones
; this will set the model for thermal analysis only
model mechanical active off
model thermal active on

; setting thermal properties, isotropic model
zone thermal cmodel isotropic
zone thermal property conductivity 7.5e-1 specific-heat 0.75e3 expansion 8e-6

; definition of thermal boundaries

; fixed or invariants thermal boundaries as inputted and saved in Slot 5
; these are mostly the zone layers at the edges of the model, but the upper surface
; such as the bottom surface of the bottom group or the back, east and west sides of the cliff, etc
; import geometry
geometry import '00Thermal_boundary\01Th_Fixed\bottom_back.stl' set 't_bottom_back'
(...)
geometry import '00Thermal_boundary\01Th_Fixed\debris_front.stl' set 't_debris_front'

; assign group and slot using the distance to geometry in meters
zone group 'BOTTOM_BACK' slot 5 range geom-distance 't_bottom_back' gap 0.005 extent
(...)
zone group 'DEBRIS_FRONT' slot 5 range geom-distance 't_debris_front' gap 0.005 extent

; assign a fixed temperature to these groups
zone face apply temperature 15.0 range group 'BOTTOM_BACK' slot 5
(...)
zone face apply temperature 15.0 range group 'DEBRIS_FRONT' slot 5

; Boundaries which location and extension that do not change over the year,
; yet their value is not constant and numerically change with certain functions
; temperature values are assigned after function definitions
```

; input geometry

```
geometry import '00Thermal_boundary\02Th_NOseasonal\cliff_front_C.stl' set 't_cliff_front_C'
(...)
```

```
geometry import '00Thermal_boundary\02Th_NOseasonal\slab3_west.stl' set 't_SLAB3_WEST'
```

; assign group and slot using the distance to geometry in meters

```
zone group 'CLIFF_FRONT_CENTRE' slot 5 range geom-distance 't_cliff_front_C' gap 0.005 extent
(...)
```

```
zone group 'SLAB3_WEST' slot 5 range geom-distance 't_SLAB3_WEST' gap 0.005 extent
```

; create the thermal regions on the joints and save them in Slot 6

; to simulate different thermal properties due to discontinuity

; review line in Appendix 6-b for joint/interface creation

```
zone group 'JOINT1_COL' slot 6 range interface 'INT1C0'
```

```
(...)
```

```
zone group 'JOINT3_N3' slot 6 range interface 'INT3N3'
```

; assign different thermal properties to these zones

```
zone thermal property conductivity 7.5e-3 specific-heat 0.75e3 expansion 8e-7 range
```

```
.....group 'JOINT1_COL' slot 6
```

```
(...)
```

```
zone thermal property conductivity 7.5e-3 specific-heat 0.75e3 expansion 8e-7 range
```

```
.....group 'JOINT3_N3' slot 6
```

; define the thermal boundaries that change between summer and winter

; definition based on geometry and regions such as high, middle and low

; with a geometry range command, distance in meters

; groups are saved in Slot 7

; summer boundaries

```
geometry import '00Thermal_boundary\04Th_SUMMER\BS_highT.stl' set 'BS_highT'
```

```
geometry import '00Thermal_boundary\04Th_SUMMER\BS_lowT.stl' set 'BS_lowT'
```

```
geometry import '00Thermal_boundary\04Th_SUMMER\BS_midT.stl' set 'BS_midT'
```

```
zone group 'SUM_highT' slot 7 range geom-distance 'BS_highT' gap 0.025 extent
```

```
zone group 'SUM_lowT' slot 7 range geom-distance 'BS_lowT' gap 0.025 extent
```

```
zone group 'SUM_midT' slot 7 range geom-distance 'BS_midT' gap 0.025 extent
```

; winter boundaries, saved in Slot 8

```
geometry import '00Thermal_boundary\05Th_WINTER\BW_lowT.stl' set 'BW_lowT'
```

```
geometry import '00Thermal_boundary\05Th_WINTER\BW_midT.stl' set 'BW_midT'
```

```

zone group 'WIN_lowT' slot 8 range geom-distance 'BW_lowT' gap 0.025 extent
zone group 'WIN_midT' slot 8 range geom-distance 'BW_midT' gap 0.025 extent

```

```

; thermal functions to input assign transient temperature values
; to boundary conditions are defined using thermal.time.total
; there are 3 main functions TRT for top/high region LRT for low region
; and MRT for middle region which changes month by month

```

```

fish define TRT
  global TRT
  TRT = 10*(math.sin(2.0*math.pi*((thermal.time.total)/(3600*24*365))- 1.7)+3)
  .....+ 17*(math.sin(2.0*math.pi*((thermal.time.total)/(24*3600))- 2.0) - 0.0)
end

```

```

fish define LRT
  global LRT
  LRT = 8.0*(mat.sin(2.0*math.pi*((thermal.time.total)/(24*365*3600))- 1.7)+2.1)
  .....+ 8*(math.sin(2.0*math.pi*((thermal.time.total)/(24*3600))- 2.0) - 0.0)
end

```

```

fish define MRT01
  global MRT01
  MRT01 = 15.0*(math.sin(2.0*math.pi*((thermal.time.total)/(24*365*3600))- 1.6)+1.5)
  .....+ 8*(math.sin(2.0*math.pi*((thermal.time.total)/(24*3600))- 2.0) + 0)
end

```

(...)

```

fish define MRT07
  global MRT07
  MRT07 = 15.0*(math.sin(2.0*math.pi*((thermal.time.total)/(24*365*3600))- 1.6)+1.5)
  .....+ 15*(math.sin(2.0*math.pi*((thermal.time.total)/(24*3600))- 2.0) - 0)
end

```

(...)

```

fish define MRT12
  global MRT12
  MRT12 = 15.0*(math.sin(2.0*math.pi*((thermal.time.total)/(24*365*3600))- 1.6)+1.5)
  .....+ 8*(math.sin(2.0*math.pi*((thermal.time.total)/(24*3600))- 2.0) + 0)
end

```

```

; create thermal histories to initialize functions
; and to track the temperature records of zones
; thermal age history is created for simulation purposes

```

model history name 'thtime' thermal time-total
model history name 'thage' thermal age

fish history name 'TRT' TRT
fish history name 'LRT' LRT
fish history name 'MRT01' MRT01
(...)
fish history name 'MRT07' MRT07
(...)
fish history name 'MRT12' MRT12

; track temperature at the sensor location
zone history name 'FO-Temp' temperature position (0.191865,-0.836707,5.48913)

; create histories for other locations shown on sections in Appendix 6-c
zone history name '1100-TEMP' temperature zoneid 2004033
(...)
zone history name '9905-TEMP' temperature zoneid 976502

; model with new settings is saved
model save '03TMmodel\Run01_TM00.sav'

; for thermal analysis the model needs to be assigned with a density
; in all its zones, if one zone has null density then model will not run
; so to ensure this a function is run to assign same density across the entire model
; even at the debris layer which had a smaller density value

fish define density
 local Z
 loop foreach Z zone.list
 zone.density (Z)= 2000
 endloop
end
@density

; thermal implicit conditions are set to allow larger time steps, fixing its value
; in this case, every second in computational time corresponds to 150 s in simulation
zone thermal implicit on
model thermal timestep fix 150

; histories are queried every 10 steps
history interval = 10
; an initial condition must be set at time = 0
zone face apply temperature = 1 fish MRT01 range group 'WIN_midT' slot 8

```
;Time per month in seconds needs to be assign as a constant value
;this time will limit the thermal total time
;functions will allow the model to run until time is reached as a condition
```

```
fish define zTime_201801
  global CurrTime = thermal.time.total

  if CurrTime<= 2678400
    return false
  else
    return true
  endif
end
(...)
```

```
fish define zTime_202307
  global CurrTime = thermal.time.total

  if CurrTime<= 176083200
    return false
  else
    return true
  endif
end
```

```
; model is saved before running solution
model save '03TMmodel\Run01_TM01.sav'
```

```
;Then each month is run by using the command fish-halt until
;thermal total time is reached
```

```
call '01Thermal_Sequence\ThB_01_January.dat'
model solve fish-halt @zTime_201801
@extraVar
model save '03TMmodel\Run001_001_201801.sav'
(...)
```

```
call '01Thermal_Sequence\ThB_07_July.dat'
model solve fish-halt @zTime_202307
@extraVar
model save '03TMmodel\Run001_067_202307.sav'
```



```
;;; This is the end of the model.  
;;; Note that each ThB file assigns boundary conditions.  
;;; Below 2 examples of boundary conditions, using the groups in corresponding slots
```

```
;;;Boundary conditions for January
```

```
;Top Region Temperature - TRT  
zone face apply-remove temperature range group 'DEBRIS_UP' slot 5  
zone face apply temperature = 1 fish TRT range group 'DEBRIS_UP' slot 5
```

```
;Middle Region Temperature - MRT  
zone face apply-remove temperature range group 'WIN_midT' slot 8  
zone face apply-remove temperature range group 'WIN_lowT' slot 8
```

```
zone face apply temperature = 1 fish MRT01 range group 'WIN_midT' slot 8  
zone face apply temperature = 1 fish LRT range group 'WIN_lowT' slot 8
```

```
;Low Region Temperature - LRT  
zone face apply-remove temperature range group 'CLIFF_FRONT_CENTRE' slot 5  
zone face apply-remove temperature range group 'J1N1_EXC' slot 5  
zone face apply-remove temperature range group 'LAT_FRAC_BACK' slot 5  
zone face apply-remove temperature range group 'LAT_FRAC_UP' slot 5  
zone face apply-remove temperature range group 'NOTCH_BACK' slot 5
```

```
zone face apply temperature = 1 fish LRT range group 'CLIFF_FRONT_CENTRE' slot 5  
zone face apply temperature = 1 fish LRT range group 'J1N1_EXC' slot 5  
zone face apply temperature = 1 fish LRT range group 'LAT_FRAC_BACK' slot 5  
zone face apply temperature = 1 fish LRT range group 'LAT_FRAC_UP' slot 5  
zone face apply temperature = 1 fish LRT range group 'NOTCH_BACK' slot 5
```

```
;Functions will change between months  
zone face apply-remove temperature range group 'LAT_FRAC_FRONT' slot 5  
zone face apply-remove temperature range group 'PIT_BOTTOM' slot 5  
zone face apply-remove temperature range group 'DEBRIS_PIT' slot 5
```

```
zone face apply temperature = 1 fish LRT range group 'LAT_FRAC_FRONT' slot 5  
zone face apply temperature = 1 fish LRT range group 'PIT_BOTTOM' slot 5  
zone face apply temperature = 1 fish LRT range group 'DEBRIS_PIT' slot 5
```

```
;;; Boundary conditions for July
```

;Top Region Temperature - TRT

zone face apply-remove temperature range group 'DEBRIS_UP' slot 5

zone face apply temperature = 1 fish TRT range group 'DEBRIS_UP' slot 5

;Middle Region Temperature - MRT

zone face apply-remove temperature range group 'SUM_highT' slot 7

zone face apply-remove temperature range group 'SUM_midT' slot 7

zone face apply-remove temperature range group 'SUM_lowT' slot 7

zone face apply temperature = 1 fish TRT range group 'SUM_highT' slot 7

zone face apply temperature = 1 fish MRT07 range group 'SUM_midT' slot 7

zone face apply temperature = 1 fish LRT range group 'SUM_lowT' slot 7

;Low Region Temperature - LRT

zone face apply-remove temperature range group 'CLIFF_FRONT_CENTRE' slot 5

zone face apply-remove temperature range group 'J1N1_EXC' slot 5

zone face apply-remove temperature range group 'LAT_FRAC_BACK' slot 5

zone face apply-remove temperature range group 'LAT_FRAC_UP' slot 5

zone face apply-remove temperature range group 'NOTCH_BACK' slot 5

zone face apply temperature = 1 fish LRT range group 'CLIFF_FRONT_CENTRE' slot 5

zone face apply temperature = 1 fish LRT range group 'J1N1_EXC' slot 5

zone face apply temperature = 1 fish LRT range group 'LAT_FRAC_BACK' slot 5

zone face apply temperature = 1 fish LRT range group 'LAT_FRAC_UP' slot 5

zone face apply temperature = 1 fish LRT range group 'NOTCH_BACK' slot 5

;Functions will change between months

zone face apply-remove temperature range group 'LAT_FRAC_FRONT' slot 5

zone face apply-remove temperature range group 'PIT_BOTTOM' slot 5

zone face apply-remove temperature range group 'DEBRIS_PIT' slot 5

zone face apply temperature = 1 fish MRT07 range group 'LAT_FRAC_FRONT' slot 5

zone face apply temperature = 1 fish MRT07 range group 'PIT_BOTTOM' slot 5

zone face apply temperature = 1 fish MRT07 range group 'DEBRIS_PIT' slot 5

APPENDIX G

```
; The following script details the commands to set the thermo-mechanical conditions for  
; a given mechanical solution in FLAC3D  
; FLAC34 V7.00.157  
; Rodrigo Alcaino-Olivares & Matthew A. Perras  
; Developed in 2022 – 2024
```

```
; restore the mechanical model to run  
; for this example, an elastic case with plastic joints  
model restore '02BaseModel\Run01_elasticWjoints.sav'
```

```
; deactivate the mechanical configuration and activate the thermal ones  
; this will set the model for thermal analysis only  
model mechanical active off  
model thermal active on
```

```
;;; run the thermal command detailed in Appendix 6-f.  
;;; Check thermal settings  
;;; include the thermal total time fish function
```

```
; model is saved before running solution  
model save '03TMmodel\Run001_TM01.sav'
```

```
; activate both mechanical and thermal configurations
```

```
model mechanical active on  
model thermal active on
```

```
;run the simulations  
call '01Thermal_Sequence\ThB_01_January.dat'  
model solve fish-halt @zTime_201801  
@extraVar  
model save '03TMmodel\Run001_001_201801.sav'  
(...)
```

```
call '01Thermal_Sequence\ThB_07_July.dat'  
model solve fish-halt @zTime_202307  
@extraVar  
model save '03TMmodel\Run001_067_202307.sav'
```

APPENDIX H

Appendix H - 1: Input parameters for several simulations introduced in Chapter 8.

Run ID	Rock Mass Stiffness		Rock Mass Strength				Joint Stiffness and Strength								Thermal Properties				Constitutive Model (Elastic or Plastic Solution)
	E (GPa)	ν	UCS (MPa)	σ_t (MPa)	Dil.	GSI	Kn (GPa/m)	Ks (GPa/m)	θ	Dil.	Coh. (MPa)	Ten. (MPa)	SBR	LF	K rock (W/mK)	K joint (W/mK)	T.E. rock (1/°C)	T.E. joint (1/°C)	
T-001	3.94	0.21	15	8		60	210	21	35	30			50	Y	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁶	Plasticity: All.
T-002	3.94	0.21					210	21	35	30			50	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Elastic solution
T-003	3.94	0.21					210	21	35	30			50	Y	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Elastic solution
T-004	3.94	0.21	15	8		60	210	21	35	30			50	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Plasticity: LF
T-005	3.94	0.21	15	8		60	210	21	35	30			50	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Plasticity: LF, Slab1.
T-006	3.94	0.21	15	8		60	210	21	35	30			50	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Plasticity: LF, Slab1, Notch 1.
T-007	3.94	0.21	15	8		60	210	21	35	30			50	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Plasticity: LF, Notch 1.
T-008	3.94	0.21	15	8		60	210	21	35	30			50	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Plasticity: LF, Notch 1, Notch 2.
T-009	3.94	0.21	15	8		60	210	21	35	30			50	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Plasticity: LF, Slab2.
T-010	3.94	0.21	15	8		60	210	210	35	30			50	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Plasticity: LF, Slab2.
T-011	3.94	0.21	15	8		60	210	21	35	30			50	Y	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Elastic: Slab 1, Notch 1. Plastic: other groups.
T-012	3.94	0.21				60	10	4	35	30			50	Y	0.75	0.0075	8x10 ⁻⁵	8x10 ⁻⁷	Elastic Solution
T-013	3.94	0.21				60	20	10	35	30			50	Y	0.75	0.0075	8x10 ⁻⁵	8x10 ⁻⁷	Elastic Solution
T-014	3.94	0.21				60	210	21	35	30			50	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Elastic Solution
T-015	3.94	0.21				60	210	42	35	30			50	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Elastic Solution
T-016	3.94	0.21				60	210	21	35	30			50	N	0.75	0.0075	5x10 ⁻⁵	8x10 ⁻⁷	Elastic Solution
T-017	3.94	0.21				60	210	21	35	30			50	N	0.75	0.0075	2x10 ⁻⁵	8x10 ⁻⁷	Elastic Solution
T-018	3.94	0.21	15	8		60	210	21	35	30			50	N	0.75	0.0075	2x10 ⁻⁵	8x10 ⁻⁷	Plasticity: All
T-019	3.94	0.21				60	210	21	35	30			50	N	0.75	0.0075	2x10 ⁻⁵	2x10 ⁻⁷	Elastic Solution
T-020	3.94	0.21				60	168	42	35	30			50	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Elastic Solution
T-021	3.94	0.21				60	630	63	35	30			50	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Elastic Solution
T-022	3.94	0.21				60	210	210	35	30			50	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁶	Elastic Solution
T-023	3.94	0.21				60	210	21	35	30			50	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁶	Elastic Solution
T-024	3.94	0.21				60	210	21	35	30			50	N	0.75	0.0075	5x10 ⁻⁵	5x10 ⁻⁵	Elastic Solution
T-025	3.94	0.21				60	210	21	35	30			50	N	0.75	0.75	8x10 ⁻⁶	8x10 ⁻⁶	Elastic Solution
T-026	3.94	0.21				60	210	21	35	30			50	N	0.75	0.75	5x10 ⁻⁵	8x10 ⁻⁶	Elastic Solution
T-027	3.94	0.21				60	210	210	35	30			50	N	0.75	0.75	8x10 ⁻⁶	8x10 ⁻⁶	Elastic Solution
T-028	3.94	0.21				60	210	21	35	30			50	N	0.75	0.75	5x10 ⁻⁵	5x10 ⁻⁵	Elastic Solution
T-029	3.94	0.21				60	210	210	35	30			100	N	0.75	0.0075	5x10 ⁻⁵	5x10 ⁻⁵	Elastic Solution
T-030	3.94	0.21				60	210	21	35	30			100	N	0.75	0.0075	5x10 ⁻⁵	5x10 ⁻⁵	Elastic Solution

Appendix H - 2: Table continuation.

Run ID	Rock Mass Stiffness		Rock Mass Strength				Joint Stiffness and Strength								Thermal Properties				Constitutive Model (Elastic or Plastic Solution)
	E (GPa)	ν	UCS (MPa)	σ_t (MPa)	Dil.	GSI	Kn (GPa/m)	Ks (GPa/m)	θ	Dil.	Coh. (MPa)	Ten. (MPa)	SBR	LF	K rock (W/mK)	K joint (W/mK)	T.E. rock (1/°C)	T.E. joint (1/°C)	
T-031	3.94	0.21				60	210	210	35	30			100	N	0.75	0.0075	5x10 ⁻⁵	5x10 ⁻⁶	Elastic Solution
T-032	3.94	0.21				60	210	21	35	30			100	N	0.75	0.0075	8x10 ⁻⁶	8x10 ⁻⁷	Elastic Solution
T-033	3.94	0.21				60	210	210	35	30			100	N	0.75	0.0075	2x10 ⁻⁵	2x10 ⁻⁶	Elastic Solution
T-034	3.94	0.21				60	210	210	35	30	1	7	100	N	0.75	0.0075	3x10 ⁻⁵	3x10 ⁻⁶	Elastic Solution
T-035	3.94	0.21				60	210	210	35	30	1	7	100	N	0.75	0.0075	3x10 ⁻⁵	3x10 ⁻⁸	Elastic Solution
T-036	3.94	0.21				60	210	210	35	30	1	7	100	N	0.75	0.0075	5x10 ⁻⁵	5x10 ⁻⁸	Elastic Solution
T-037	3.94	0.21				60	210	210	35	30	1	7	100	N	0.75	0.0075	7x10 ⁻⁵	7x10 ⁻⁸	Elastic Solution
T-038	3.94	0.21				60	210	210	35	30	1	7	100	N	0.75	0.0075	1x10 ⁻⁴	1x10 ⁻⁷	Elastic Solution
T-039	3.94	0.21				60	210	210	35	30	1	7	100	Y	0.75	0.0075	7x10 ⁻⁵	7x10 ⁻⁸	Elastic Solution
T-040	3.94	0.21				60	210	21	35	30	1	7	100	N	0.75	0.0075	5x10 ⁻⁵	5x10 ⁻⁸	Elastic Solution
T-041	3.94	0.21	15	8		60	210	21	35	30	1	7	100	N	0.75	0.0075	7x10 ⁻⁵	7x10 ⁻⁸	Plasticity: LF.
T-042	9.72	0.21	55.6	10		70	210	21	35	30	1	7	100	N	0.75	0.0075	7x10 ⁻⁵	7x10 ⁻⁸	Plasticity: LF.
T-043	9.72	0.21	55.6	10		70	210	21	35	30	1	10	100	N	0.75	0.0075	7x10 ⁻⁵	7x10 ⁻⁸	Plasticity: LF, Notch 1.
T-044	9.72	0.21	35	7		70	210	21	35	30	1	10	100	N	0.75	0.0075	7x10 ⁻⁵	7x10 ⁻⁸	Plasticity: Notch 1. Smaller stiffness in Notch 1
T-045	9.72	0.21	55.6	7		70	210	21	35	30	1	10	100	N	0.75	0.0075	7x10 ⁻⁵	7x10 ⁻⁸	Plasticity: Notch 1.
T-046	9.72	0.21	35	7		70	210	21	35	30	1	10	100	N	0.75	0.0075	7x10 ⁻⁵	7x10 ⁻⁸	Plasticity: Notch 1.
T-047	9.72	0.21	35	7	25	70	210	21	35	30	1	10	100	N	0.75	0.0075	7x10 ⁻⁵	7x10 ⁻⁸	Plasticity: Notch 1. Greater stiffness in upper Slab 1.
T-048	9.72	0.21	55.6	7	25	70	210	21	35	30	1	10	100	N	0.75	0.0075	7x10 ⁻⁵	7x10 ⁻⁸	Plasticity: Notch 1. Greater stiffness in upper Slab 1.
T-049	9.72	0.21	35	7	25	70	210	21	35	30	0.5	10	100	N	0.75	0.0075	7x10 ⁻⁵	7x10 ⁻⁸	Plasticity: Notch 1.
T-050	3.94	0.21				60	210	21	35	30	0.5	10	100	N	0.75	0.0075	7x10 ⁻⁵	7x10 ⁻⁸	Elastic Solution

