Temperature changes analysis in jointed rock mass to investigate effects driving slope instabilities at the Acuto field laboratory (Italy)

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1. The Acuto field laboratory

The susceptibility of natural and anthropic rock slopes to thermally-induced effects is significantly constrained by the nature and distribution of continuous and transient thermal stresses as well as by rock matrix and fracture mechanics. In various climatic contexts, temperature fluctuations interact with rock masses by exerting slight yet repeated perturbations of local stress fields, resulting in a progressive and cumulative effect (Gunzburger et al., 2005). The cyclic repetition of surface thermal stresses can determine the periodic alternation of thermal expansions and contractions of the rock matrix. This mechanism can drive joint shear movements, ultimately provoking the progressive deterioration of the mechanical properties of rock masses (i.e., both at the fracture-scale and rock matrix-scale), leading these complex systems toward growing unstable conditions over wide timescales (Marmoni et al., 2020). In this framework, while subcritical crack-growth processes and stress-strain relationships (i.e., due to the action of periodic or transient stressors on rock masses) are adequately investigated through monitoring and laboratory approaches, the evaluation and prediction of timing and location of ultimate failures in extended rock cliffs are poorly explored. The comprehension of the size and time-space location of potential failure events affecting wide sectors of natural rock cliffs represents a challenging objective for mitigating geological risks to which main infrastructures are exposed, as well as to natural and cultural heritage sites. To address this research topic, a multimethodological investigation encompassing integrated geotechnical and geophysical techniques, Infrared Thermography (IRT), and numerical modeling have been carried out at the Acuto field laboratory of CERI Research Centre and Sapienza University of Rome since 2015. This natural laboratory was implemented inside an abandoned quarry (Fig. 1a), within the municipality of Acuto (Central Italy), with the objective of understanding the role of environmental and anthropic factors in determining the worsening of rock mass stability conditions. In 2015, a potentially unstable 20 m^3 rock block was identified as the main target of monitoring activities (Fig. 1b). Several experimental activities were carried out since the laboratory foundation, providing new insights in data analysis and methodologies for the investigation of rock mass damaging processes and the definition of early-warning strategies for the management of landslide-related geological risks. Starting from 2018, the experimental activities of the field laboratory are funded by the Department of Excellence Project of the Italian Ministry of University and Research. In this framework, the field laboratory underwent a structural upgrade aimed at investigating two new sectors of the quarry wall and at implementing a novel integrated monitoring system. In particular, these new sectors (Fig. 1c, d) were selected because they can be considered representative of different dimensional scales and degrees of freedom to instability conditions. The new monitoring system, whose upgrade ended at the beginning of 2022, consists of a great variety of geophysical, geotechnical and environmental devices, including:

- Two fully-equipped weather stations (air thermometer, air hygrometer, rain gage, air speed and direction anemometer).
- One heat flux cell; two rock thermometers; two leaf wetness sensors; two thermal profile probes (composed by four thermocouples installed at progressively greater depths); one infrared thermal camera FLIR T-840.

- Six joint-gauges installed on open fractures; Twelve HBM strain-gauges installed on microcracks.
- One fiber Bragg grating array implemented with three baselines and nine measurement points.
- Eight three-component 10 Hz geophones set with sampling frequency of 1000 Hz; Five 4.5 Hz three-component geophones set with sampling frequency of 500 Hz; all geophones are cable-connected to dedicated digital data-loggers.
- Two three-component force balance accelerometers (EpiSensor) cable-connected to a Kinematrics Quanterra Q330 digital data-logger.
- Four Acoustic Emission (AE) 150 kHz sensors; one AE 4.5 kHz sensor (Physical Acoustics).

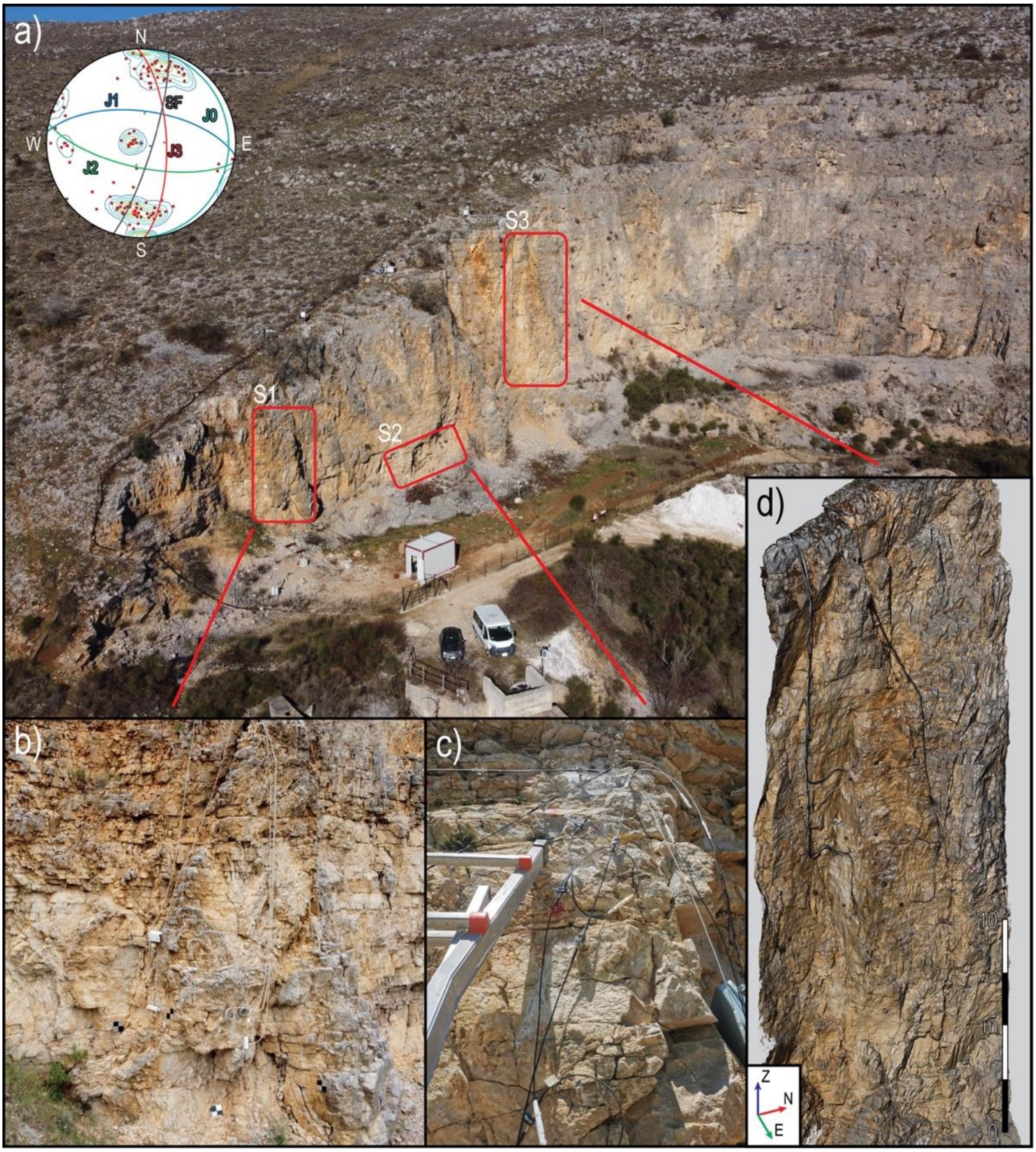

Figure 1. Panoramic view of the Acuto field laboratory where the location of the three main monitoring sectors is highlighted by red squares (S1-S2-S3) (a). In the upper-left corner the synthetic stereographic projection is also provided, representing the four main discontinuity sets (J0–J4) recognized in the quarry area (a). View of the 20 m³ jointed rock block selected in 2015 as the main target of a permanent multiparametric monitoring system (sector S1) (b). Close view of the subvertical rock wall where the FBA was installed in 2021 (sector S2) (c). 3D textured model of the 200 m³ jointed rock column that was instrumented in 2022 with a high density integrated geotechnical and geophysical monitoring system (sector S3) (d).

The monitoring system is connected to specific digital data-loggers, which allow for continuous and triggered acquisition modes. The power supply is guaranteed both by the local electrical infrastructure, solar panels and multiple backup batteries. Besides, internet services for real-time transfer of all recorded data to a cloud storage server, located inside the Department of Earth Sciences of Sapienza University, are guaranteed by a radio link.

2. Main outcomes and future perspectives

Thermal forcings have revealed the most active and effective in cumulating strain on rock surfaces. To frame its contribution and quantify the behavior of the jointed rock mass, the direct monitoring was integrated by daily and seasonal remote IRT surveys, which allows to better constrain the thermal effects on rock mass through the evaluation of the role of solar paths, direct radiation, and shadowing over the complex rock surface (Fiorucci et al. 2018). In this preliminary approach, the thermal-insulation role played by open joints in the propagation of heat waves within the thermal active layer (TAL) was discussed, opening a new perspective in the study of thermally-induced effects on jointed rock mass (Fig. 2g). To infer the 3D interaction between the solar radiation and exposed rock masses, a new approach integrating IRT and SfM to generate 3D thermal point clouds was implemented by Grechi et al. 2021 (Fig. 2h). The authors showed that the potential of this novel approach lies in the possibility of obtaining interactive models that can describe surface temperature fluctuations of target elements and deepen the existing relationships between morphological features of rock masses and their continuously varying thermal boundary conditions. On the IRT outcomes and experimental evidence, a 2D coupled thermomechanical analysis was conducted availing of the ode FLAC 7.0 2D Itasca Cons. by parametrically reproducing the joint mechanical properties as mesh interfaces and optimally tuning the modeled temperature and strain data with respect to the monitored ones (Fig. 2a-c). The main modeling outcomes highlighted the importance of joint set attitude and location in controlling temperature distribution at the daily and seasonal timescales. Combined numerical modeling allowed us to infer the importance of thermal contrasts across joints in the evolution of plasticity on weak joints (Marmoni et al. 2020). The thermomechanical analysis allowed us to characterize the cyclic contraction and relaxation response of major rock fractures and microcracks to the experienced temperature fluctuations under representative climatic conditions and non-ordinary weather events.

The microseismic monitoring carried out during an extreme meteorological event that affected Mediterranean Europe (namely *Buran*) highlighted the concentration of several MS events in correspondence of persistent freezing conditions of the jointed rock mass (Fig. 2d, e). Micro-seismic activity preceded a rockfall event of about 1 m^3 that detached close to the monitored rock block. Such a failure event was automatically detected through a change detection algorithm embedded into an AI optical camera (D'Angiò et al. 2021). The long-term monitoring instead (Fig. 2f) pointed out how low-frequency MS signals can be attributed to different driving mechanisms under subcritical and critical regimes as a consequence of either thermal dilation and contraction cycles (i.e., thermal fatigue) or freezing-thawing mechanisms (Grechi 2022).

In this perspective, the newly deployed AE-sensors and the dedicated FBG-array will broaden the frequency band and observation level in jointed rock masses, opening new scenarios for thermomechanical studies. The large amount of monitoring data, which will be collected in the future, can be analyzed and managed almost automatically and in near real-time, thanks to specific machine learning customized applications. Starting from the already acquired knowledge over the past six years on thermo-elastic effects affecting the rock mass at different spatial and temporal scales (Fiorucci et al. 2020), the statistical analysis of inelastic deformations can be performed through an artificial neural network (ANN). This approach will also allow for predicting cause-to-effect relationships between multiple environmental factors and induced strains and the onset of plastic deformation events that could anticipate and drive the failure stages (i.e., rockfalls).

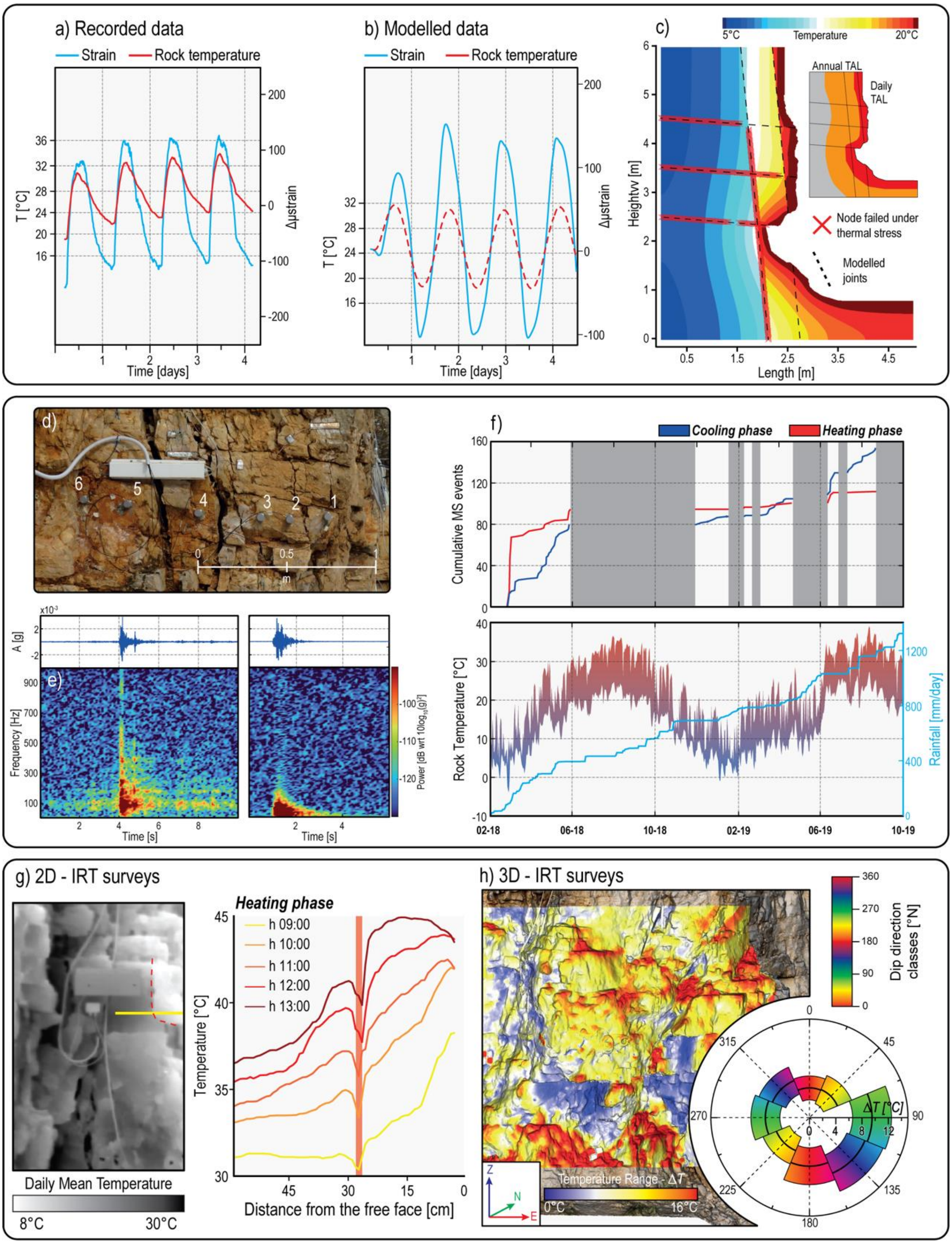

Figure 2. In-situ recorded data and numerical modeling results (a, b). Contour plot of the thermomechanical model with the plasticized nodes under cyclic thermal loading (c) (modified from Marmoni et al. 2020). Lateral view of the monitored rock block with the linear array composed of six one-component microaccelerometers deployed starting from February 2018 (d). Examples of two MS events (e) (modified from D'Angiò et al. 2021). Comparison between environmental factors and the distribution of MS events during heating and cooling phases of the rock mass (f): the distinction between heating (in red) and cooling (blue) phases of the rock mass is proposed to investigate the response of the rock mass to different thermal regimes (Grechi 2022). 2D distribution of daily mean temperatures, derived from IRT surveys, along with thermal profiles computed during the heating phase of the rock block along a cross-section (yellow line) intersecting an open fracture (red area) (g) (modified from Fiorucci et al. 2018). 3D thermal point cloud of the rock block with the relative polar plot representing absolute values of daily thermal ranges as a function of dip direction classes (h) (modified from Grechi et al. 2021).

References

D'Angiò, D, Fantini, A, Fiorucci, M, Iannucci, R, Lenti, L, Marmoni, GM, Martino, S, 2021. Environmental forcings and micro-seismic monitoring in a rock wall prone to fall during the 2018 Buran winter storm: Natural Hazards, v. 106, p. 2599–2617.

Fiorucci, M, Marmoni, GM, Martino, S, Mazzanti, P, 2018. Thermal Response of Jointed Rock Masses Inferred from Infrared Thermographic Surveying (Acuto Test-Site, Italy): Sensors, v. 18, 2221.

Fiorucci, M, Martino, S, Bozzano, F, Prestininzi, A, 2020. Comparison of approaches for data analysis of multi-parametric monitoring systems: insights from the Acuto test-site (Central Italy). Applied Sciences, v. 10, 7658.

Grechi, G, Fiorucci, M, Marmoni, GM, Martino, S, 2021. 3D Thermal Monitoring of Jointed Rock Masses through Infrared Thermography and Photogrammetry: Remote Sensing, v. 13, 957.

Grechi, G 2022. Nonlinear strain effects induced by thermal forcing on jointed rock masses. Ph.D. Thesis. Sapienza University of Rome, Department of Earth Sciences.

Gunzburger, Y, Merrien-Soukatchoff, V, Guglielmi, Y, 2005. Influence of daily surface temperature fluctuations on rock slope stability: Case study of the Rochers de Valabres slope (France): International Journal of Rock Mechanics and Mining Sciences, v. 42, p. 331–349.

Marmoni, GM, Fiorucci, M, Grechi, G, Martino, S, 2020. Modelling of thermo-mechanical effects in a rock quarry wall induced by near-surface temperature fluctuations: International Journal of Rock Mechanics and Mining Sciences, v. 134, p. 104440.