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## Role of Positive Temperature Variations on Rock Slopes Outcrops (a review)

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**SUMMARY:** The role of positive temperature fluctuations on the destabilisation or displacement of rock slopes is increasingly mentioned. The abstract identifies and classifies the related publications, involving *in situ* sites, according to observations, measurements, explaining mechanisms and outlines some challenges to be addressed in the coming years.

**Keywords:** rock, slope, thermomechanics fracture, *in situ*

### Introduction

Thermomechanical surface effects on rock outcrops are increasingly quoted in the last twenty years. This abstract aims to list the publications around this theme, involving *in situ* sites (excluding laboratory experiments), and to and classify them according to observations, measurements and possible mechanisms, before issuing a few comments on the subject.

### Observations

The direct link between positive temperature variations and rockfalls or rockslides has begun to be often quoted in the, 2000s, although since the 1930s there have been discussions among geomorphologists about the role of temperature on weathering. Gunzburger et al. (2004) and Vargas et al. (2004) were among the first authors to point the role of temperature in deep failure. Vargas et al. (2013) reported variable volume events associated with considerable daily fluctuations in maximal and minimal temperatures: small superficial volume, mainly composed of thin slab failure, but also large rock falls. Quoted thermally induced stresses failures can then be differentiated in two categories: shallow versus depth events. Superficial events, also called spalling, onionskin layers or exfoliation sheets, and which we can probably qualify as weathering, some mm<sup>3</sup> to a m<sup>3</sup> are described by (Vargas et al., 2004, Leith et al., 2017, Collins and Stock, 2016, Alcaino-Olivares et al., 2021, Lamp et al., 2017) whereas important volumes (from 420 to at least 2,500 m<sup>3</sup>) of rock instability are quoted by (Vargas et al., 2013, Gischig et al., 2011a, Gischig et al., 2011b, Gunzburger et al., 2005, Gasc-Barbier and Merrien-Soukatchoff, 2019). Small events have the advantage of being recurrent and it is therefore possible to make observations and measurements where they occur, but they can rather be qualified as weathering. The large events, classified as rockfalls, are generally isolated and even if observations and instruments are placed on the site immediately, the phenomena are unlikely to recur quickly. Yet, considering the risk the latter are much more important. Due, among others, to the lack of meteorological data on the site and at the time of the failure events, it is not that easy to establish whether there is a continuum between these 2 two categories (small and large volume).

### Measurements

Beside observations, *in situ* measurement are expanding. Temperature, displacement, strain or fracture opening can be measured.

Air temperature measurements are frequent, measurements in the rock itself, especially at depth, are much less numerous. Without being exhaustive, we can cite some of these measures. Coutard and Francou (1989) measure temperatures up to 48 cm deep in two alpine French sites. Messenzehl and Dikau (2017) made temperature measurement in the Swiss Alps. Gruber et al. (2004) were also interested in alpine temperature and the depth of frost. Contrariwise, Jenkins and Smith (1990) measure subsurface temperature in the Canary Islands, a much warmer environment. Molaro and McKay (2010) produce high-frequency rock subsurface temperature data from hyper-arid desert environments, an even warmer environment. They were able to detect  $dT/dt$  maximum of  $137^{\circ}\text{C min}^{-1}$ , but on a sampling interval of 0.375 s. In a more temperate zone, Safanda (1999) measures temperature in boreholes in Krušné Hory Mountains of Czech Republic with depth varying from 30 to 60 cm. He insists that the ground surface temperatures are strongly dependent on the slope angle and orientation. This was confirmed by Gunzburger and Merrien-Soukatchoff (2011) who show the influence of the air temperature and solar radiation on ground and depth temperature in the Valabres site. Gasc-Barbier et al. (2021) measured temperature up to 6 m depth from a cliff wall. Sometimes rock temperature at the surface is deduced from infrared thermography (Fiorucci et al., 2018). These measurements generally raise problems concerning the equipment used for the measurements: the insulation of the borehole and therefore the validity of the measurements. Spot measurements are generally insufficient; frequent and reliable measurements are needed (without drift over time) over long periods, which sets the problem of the stability of the equipment and the funds to allow this. Some in-depth measurements are combined with measurements of solar radiation (Grøneng et al., 2011) which is quite rare on the slopes.

Measurement of displacement related to temperature can be separated in measurement including the whole rock mass or displacement along fractures. Krähenbühl (2004), Gunzburger et al. (2004), Watson et al. (2004) and Gunzburger et al. (2005) quote global movement of the rock mass. The full range of surface measurements such as Lidar, infrared thermography (Guerin et al., 2020), photogrammetry, Ground-Based Radar are possibly used to look after the topographic variation, but the topographic measurement could be unable to measure the displacement in the absence of fractures involved in this movement (Gunzburger et al., 2005). Numerous authors measure of temperature variations along existing fissures associated with their aperture (Vlcko et al., 2009, Grøneng et al., 2011, Gischig et al., 2011b, Bakun-Mazor et al., 2011, Mufundirwa et al., 2011, Bakun-Mazor et al., 2013, Cloutier et al., 2015, Collins et al., 2018, Taboada et al., 2017, Gasc-Barbier et al., 2021, Marmoni et al., 2020). These measures are always superficial due to the difficulty of instrumenting deep cracks and in some of these measurements the problem of the possible drift of the instruments themselves is not clearly excluded. Measurements of angle deviation through inclinometers are also sometimes quote (Clément, 2008, Gischig et al., 2011b).

Extensometric measurements or strain gauges are less frequent but are generally associated with in-depth temperature measurement. They measure the strain on bases of a few centimetres (Clément et al., 2008) to a few metres. When the strain is measured with extensometers, they are likely to cross fractures which have an effect on the deformation but also on the field of temperature in the borehole drilling.

Many measurements are spot and superficial and raise the problem of their integration in a whole conceptual model. Only extensometers accumulate strain over a thickness and allow to the understanding of the in deep mechanism. The measurements raise the question of how these different pieces of information, rather on the surface could be combined to move on to a global mechanism in modelling. The instruments can influence how the issue is considered. Crackmeter induces discontinuous modelling whereas extensometers and inclinometers rather continuous model.

### **Proposed Computations, Mechanisms and Modelling**

Various computations, sometimes analytical but often numerical, are proposed based on thermal or thermomechanical observation and measurements on slopes. When the models try to explain a small volume and the superficial effects, they generally consider the fracturing, whereas continuous models attempt to understand the whole slope behaviour. Some computation just explained the thermal aspects and sometimes the role of solar radiation (Gunzburger and Merrien-Soukatchoff, 2011). The thermal diffusivity can be deduced from internal temperature measurement in the rock masses. In their site (Merrien-Soukatchoff et al., 2007) mentioned that the value is twice that commonly reported in the literature, but this difference is unclearly explained.

Many thermomechanical computations (whether it concerns small or large volumes) are implemented around the idea of fracture propagation due to thermal cycles and fatigue (Clément, 2008, Vargas et al., 2009, Stock et al., 2012, Collins and Stock, 2010, Collins et al., 2018, Alcaino-Olivares et al., 2021). Eppes (2022) precise the mechanisms linked to critical or subcritical growth of fractures. She does not make any size distinction between fracture propagation, and mechanical weathering producing elastic sediments or larger volumes of rock falls. Continuous models are often used to derive a stress field that will be later used to explain fracture propagation, which can be problematic because large deep fractures involved in a large volume failure have a role in the distribution of temperatures in the rock and, moreover, the fractures modify the state of stress in the rock mass.

Discontinuous modelling is rather used to compare in situ and modelled displacement (Gunzburger et al., 2005, Bakun-Mazor et al., 2020), but this modelling raises many questions about the mechanical and thermal properties to be assigned to fractures. For example (Messenzehl and Dikau, 2017) consider that the low rock porosity and permeability in their study site may still justify using a conduction model for their study site.

### **Challenges and Conclusions**

Numerous papers are related to thermomechanical effects of positive variation on in situ sites. Doubts still remain on the importance of these phenomena on rockfalls, and the rigorous proofs of thermomechanical failure are often difficult to establish. But we are only at the beginning of the collection of all these data. Largest inventories could highlight if the division between superficial sheets failure and larger rock falls volume involving pre-existing fractures is relevant or not. The influence of temperature on the measurements themselves are to be clearly eliminated and the insolation on rock slope is not enough registered to be taken into account. Thermal properties of fractures and, beyond, of the entire rock mass are still largely unknown. The role of fracture propagation, fatigue or potential creep must be clarified. Proof of these mechanisms is hard to find, so far, we often only demonstrate their possibility through modelling.

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