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Impact of climatic variation on rock slope stability

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Abstract

Climate significantly impacts the stability of rock masses and associated engineering structures, primarily through altered water regimes, thermal variations, and shifts in the 0°C isotherm. The IPCC (2019) highlights increased global temperatures, extreme weather events, intensified precipitation, droughts, and rising sea levels, all of which affect the physical and mechanical properties of rock masses. While water-related factors like rainfall and snowmelt are major triggers for rock instabilities, some rockfall events seems to be linked to other climatic factors, such as thermal cycles and freeze-thaw processes or may have combined triggering factors.

This paper briefly reviews the key processes influencing rock mass evolution, including the impact of atmospheric water (saturation, joint lubrication, and karstification), positive thermal cycles (thermal shock and fatigue), and changes in the 0°C isotherm (permafrost thaw, cryoclasty, and freeze-thaw cycles). Field observations and laboratory experiments demonstrate that these processes degrade mechanical properties, reduce strength, and increase instability risks. However, their integration into constitutive laws remains challenging. Understanding these complex interactions is crucial for assessing and mitigating climate change impacts on rock mass stability.

Keywords

Climate, Hydric variation, Freeze-thaw cycles, Thermal fatigue, Rock slope stability.

1 Introduction

If the reality of climate change is less and less questioned, taking into account its impact on rock masses or engineering structures is much more complicated. A very synthetic summary of the latest IPCC (2019) report provides:

- average rise in global surface temperatures, but very important local changes, some areas will see their average temperature cool while others will increase,
- increase in the number of extreme weather events (storms, droughts, heat domes or, on the contrary, cold drops),
- intensification of precipitation (same amount of water annually but concentrated in a smaller number of days),
- increase in the frequency of drought periods,
- increase in catastrophic weather events (hurricanes, storms, floods),
- melting glaciers and frozen soils,
- increase in the salinity of groundwater near the coast due to rising sea levels.

These events will have a major impact on the physical and mechanical characteristics of rock masses and consequently on their mechanical stability and associated structures (underground structures, rock embankments, open-air quarries, sea cliffs, etc.). But before evaluating the effect of climate change, it is important to better describe the effect of the climate. When considering the effect of climatic variations on rock instabilities, the first thought is destabilisation following heavy rain. But water variations should not be the only ones to be considered. Indeed, Delonca et al (2014) analysed the database of rock falls that reached La Réunion principal highway and showed that while rain is the main trigger, more than 50% of events are linked to other factors. Eisbacher and Clague (1984) showed that 66% of landslides in the Alps were due exclusively to precipitation or snowmelt and 25% to anthropogenic activities or earthquakes. Ravanel et al. (2017) also in the Alps, showed an increase in rock fall events during hot summers, with this increase being related to ice melting.

Having outlined the main factors to be considered in the evolution of the rock mass, we will review the description of climate factors in terms of processes, following the work presented by the CFMR (French Rock Mechanic NG) working group on climate change (Conil et al., 2024), that is: impact of atmospheric water, positive thermal cycles, changes in the 0°C isotherm.

2 Key-factors in the evolution of the rock mass

The natural rock mass evolution over time is weathering. Its speed will depend both on the intrinsic characteristics of the rock masses and on various external factors. A summary diagram of these factors and characteristics is provided in Fig 1.

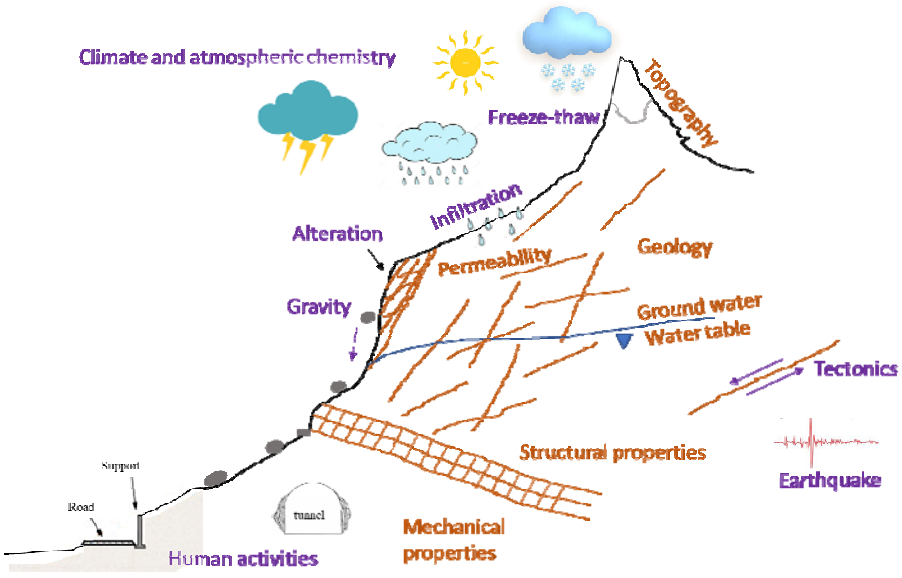


Fig. 1 Intrinsic characteristics of rock masses (brown) and main external factors (purple).

The intrinsic characteristics of the rock site under consideration, shown in brown in Fig 1, include:

- Geological and mineralogical nature of the rock as well as hydrogeological and structural conditions,
- Geomorphological conditions: localisation, morphology, topography of the site (height of the slopes, their inclination exposure(s), etc...),
- Regional tectonic conditions, which will have an influence on the initial state of stress of the massif,
- "Physical" condition of the rock mass (depth of alteration, *in situ* stress, presence or absence and type of vegetation),
- Fracturing conditions of the rock mass (identification of discontinuities families, persistence and extension, fracturing density, opening and/or filling of discontinuities, etc.),
- Hydraulic conditions (permeability, drainage, etc.)
- Mechanical characteristics of the rock mass at the appropriate REV (Representative Elemental Volume) scale, i.e., constitutive laws for both the rock matrix and the joints or, if homogenisation, the properties (strength and modulus) of the homogenised rock mass.

External factors correspond to everything that will disturb the "balance" of the rock massif and will therefore influence its weathering as well as the creation of potential instabilities. They are shown in purple in Fig 1. These are mainly:

- Local climatic conditions (rain, snowmelt, freeze-thaw, sun exposure, daily and seasonal temperature ranges),
- Factors related to the water cycle (climate, precipitation, evapotranspiration or effective rainfall distribution parameters, etc.),
- Presence or absence of rivers or sea at the foot of the cliff, which will lead to mechanical erosion up to under-caving,
- Permafrost local conditions (if any),
- Seismicity and regional tectonic activity,
- Human activities.

3 Impact of water variations on rock masses

As briefly described in the introduction, climate change is already imposing, and will continue to modify the water regime in various parts of the world (IPCC (2019). We will not detail here these evolutions but we will focus on their impact on the rock mass and the rock discontinuities.

3.1 Increased of water content

Numerous studies (Zhou et al., 2016; Althaus et al., 1994 among others) have shown that when the saturation of the rock increase, its strength decrease. Pan et al.(2020) studied the influence of saturation on UCS and Young's modulus of several rock types (Fig 2). Gombert et al. (2013) and Lafrance (2016) have shown that for clayey limestones or porous rocks such as chalk, the deterioration in mechanical properties could result in a loss of up to 70% in UCS compared with the dry state.

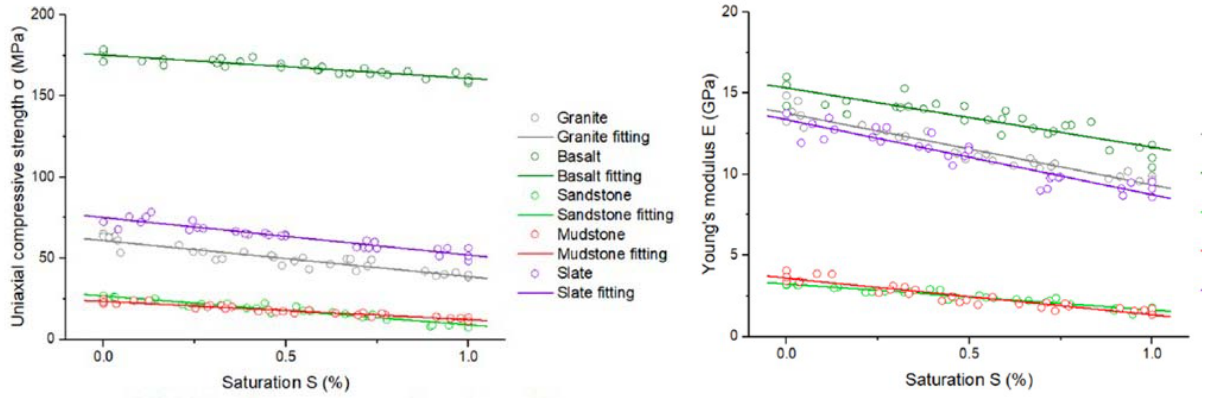


Fig. 2 Decrease in the mechanical properties of several types of rock as a function of saturation. a-simple compressive strength, b-Young's modulus after Pan et al.(2020).

3.2 Joint Lubrication or leaching

Heavy rainfall can lead to leaching of fractures, which in turn can lead to a decrease in the cohesion of discontinuities and therefore an increase in instabilities. Moreover, water has a lubricating effect on the stratification joints and fracture planes. This lubricating effect contributes to lowering the friction coefficient of discontinuities and consequently to a decrease in the strength of the rock mass (Al Heib et al., 2023; Paquette 2014). Pan et al. (2020) have for example shown that slates with a dry state friction angle between 35.5° and 44.5° have a saturated state friction angle of 30° to 36.9°.

3.3 Covering land loading

Over the main predisposing and/or triggering factors for widespread collapses of underground quarries, water and more particularly floods, very heavy rains and leaching, are in a good place (Al Heib et al. 2023). The stability of underground excavations, particularly in soft rock (limestone, calcarenite, gypsum, etc.), is significantly affected by climatic and hydrological factors such as heavy rainfall, drought (Castellanza et al., 2018).

The effects of hydraulic loading are relatively complex: rapid changes in water levels in abandoned underground caves can have opposing effects, particularly when the caves are located below the water table. If submersion occurs, as noted above, there is a decrease in the mechanical properties of sensitive rocks (unconfined compressive strength, modulus, etc.) and/or in the shear strength of submerged discontinuities, as well as an increase in pore pressure within porous rocks. Nevertheless, these effects can be mitigated by confining the pillars through hydrostatic pressure and by relieving pressure on the overlying strata.

3.4 Correlation of rainfall – slope instabilities?

The influence of rainwater infiltration on slope stability has been extensively under study in recent years (Bernardie et al., 2014; Brooks et al., 2004; Iverson, 2000; Song et al., 2020). Wang et al. (2003) pointed out that it is now proven that water is a major factor in triggering slope instabilities, with preferential circulation in rock discontinuities rather than in the rock mass. Furthermore; discontinuities often act as channels for groundwater in rock masses (Cascini et al., 2010; Djerbal & Melbouci, 2012; Raj & Sengupta, 2014; Terajima et al., 2013; Uwihirwe et al., 2020; X. Zhao et al., 2018, among others). In these cases, the water pressure depends on the density of fracture and of the joint properties such as their alteration and filling with fine materials such as clay and gouge.

However, the correlation between rainfall and landslide is not so obvious: Sandersen et al. (1997) observed that the influence of a large water supply in the last 24 hours is minimal on most rockfall events, while the water supply acting over a longer period seems to be of greater importance. However, no direct link has been established between the increase in water quantity and the movements recorded in the massif. Delonca, et al (2014) highlighted several statistical correlations between rock falls and meteorological factors, such as precipitation (daily precipitation interval, frequency of the interval) as a function of the geology and climate of the sites studied (Réunion, Burgundy, Auvergne). They confirm the link between precipitation and boulder falls in some regions, but not in others where more than 50% of events are linked to other factors (Fig 3).

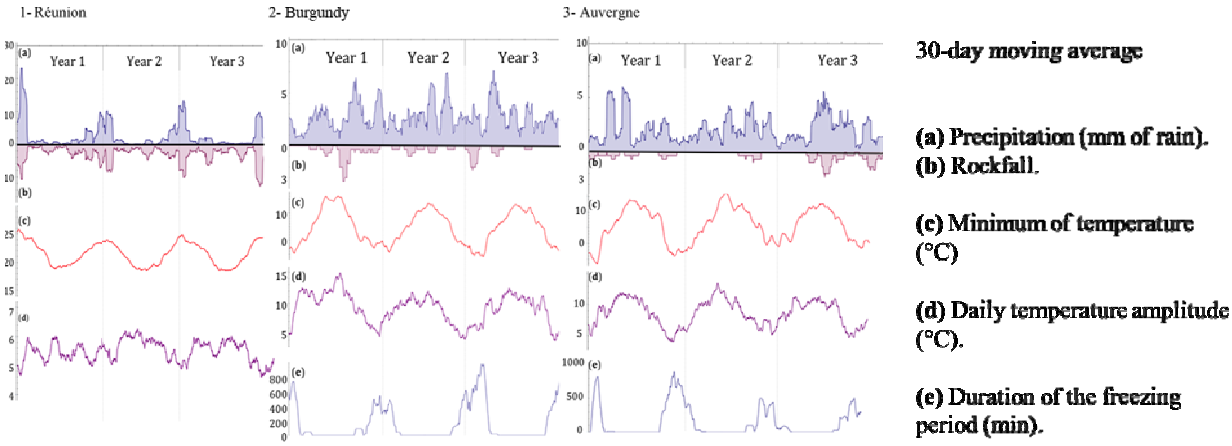


Fig. 3 Correlation between rockfalls and climatic factors, reworked from Delonca et al. (2014).

3.5 Modification of the calc-carbonic balance in the karstification process

A rather less intuitive aspect of the water table variations linked to climate change, is the changes to calc-carbonic balance in the karstification process. This phenomenon will be all the more important as the rocks are more soluble (gypsum, anhydrite).

Fig 4, inspired by Gombert (1994) shows the different stages of the karstification process. Binet et al. (2019) showed that the increase in global temperature will lead to an increase in the dissolved CO_2 content and thus modify the aggressiveness of seepage water. Similarly, increased temperatures and humidity will lead to an increase in the production of pedogenetic CO_2 which will make seepage water more aggressive and therefore disturb the calc-carbonic balance. It seems that climate change affects both hydrology, dissolution rates and mass movements, thus modifying karst patterns.

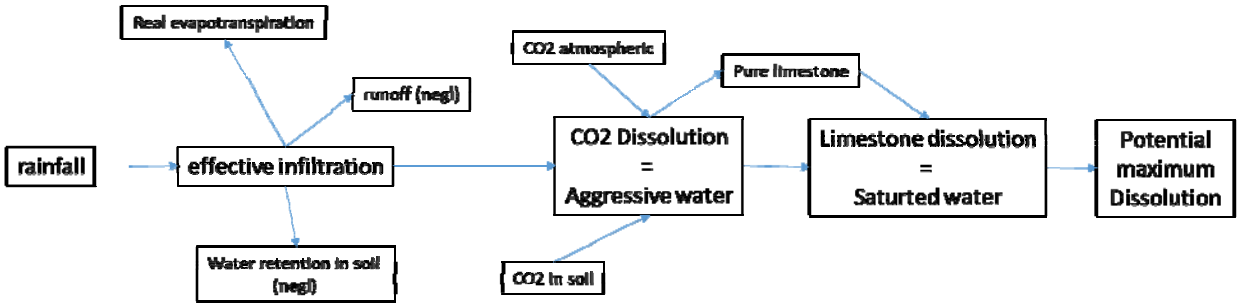


Fig. 4 The karstification process, inspired by Gombert (1994).

4 Impact of positive thermal variations on rock masses

4.1 Thermal shock

It is well known that thermal loading by temperature variation of the rock can induce inter- and intragranular micro-cracks related to the differential expansion of minerals (e.g., Fortin et al., 2018). But most of the studies carried out on this subject have been realized for temperatures well above 100°C which is not particularly relevant here. Nevertheless, they identify the phenomenon of thermal shock, which causes damage or even cracking of the rock under the influence of a sudden, large-amplitude temperature change. Hall (1999) proposes a critical thermal loading rate associated with thermal shock of approximately 2°C/min. The physical phenomenon is that related to quenching (Fortin et al., 2018), with an amplitude that will depend on the temperature variation. Classical quenching involves rapidly immersing a sample that has been heated up to 300°C in water at 20°C. The core of the sample is still hot and tends to contract, while the edges are already cold. In this case, the stresses at the edges of the sample can cause microcracks to form, extending from the edge of the sample toward its core. In the context of climatic variations, and considering the 2° threshold, it is reasonable to question whether such phenomena occur locally when (very) cold rain fall on a still-warm rock massif or in the case of wildfires fuelled by droughts.

4.2 Thermal fatigue

Beyond the effect of the punctual variation in temperature, thermal fatigue which results from repeated thermal cycles also plays an important role in the evolution of the rock mass. The oldest study found on the subject is from Grigg (1936). In recent years, more and more studies are proposing *in-situ* observations and measurements of the phenomenon (Bakun-Mazor et al., 2013; Breytenbach, 2022; Cloutier et al., 2015; Collins and Stock, 2016; Grøneng et al., 2011; Gunzburger et al., 2005; Vargas et al., 2004; Vlcko et al., 2009 among others). Merrien-Soukatchoff and Gasc-Barbier (2023) presented an up-to-date review of the measurement methods and in situ tools. Depending on the site, recording periods range from a few hours to more than a decade, and all types of rock are affected. The most commonly used measurement method involves installing crackmeters to observe the opening and closing of cracks with temperature. Fig 5 shows 2 examples for 4 days and 10 years.

Although observations and *in-situ* measurements are becoming more frequent, we still have very few experimental works to describe the corresponding mechanical behaviour (Aires-Barros, 1977; Gasc-Barbier et al., 2014; Gómez-Heras et al., 2006). Thermal fatigue significantly degrades the elastic moduli, tensile strength and uniaxial compressive strength of rocks (Villarraga et al., 2018) as well as tensile and shear parameters (Alzo'ubi and Alneasan, 2025). This damage is in fact a process of micro-

cracking caused by the combined action of differential expansion of rock constituents and local thermal gradients, both of which can give rise to high-intensity internal stresses (Hall and Thorn, 2014). Thus, while small temperature fluctuations may be considered an elastic phenomenon on a macroscopic scale, their repetition over time leads to fatigue damage, the formation or propagation of cracks, which can result in instability.

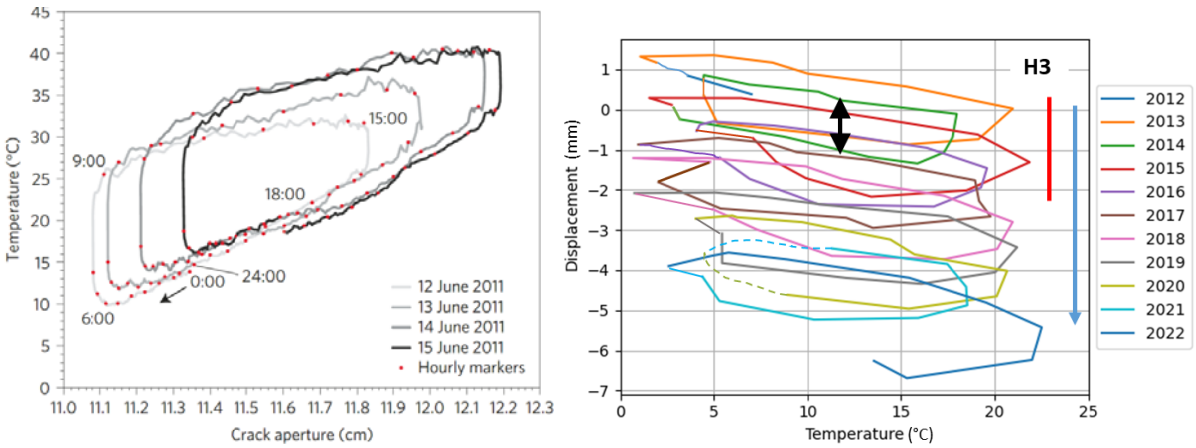


Fig. 5 Fracture openings/closures as a function of temperature. a- 4 days (Collins and Stock, 2016), b- 10 years (Gasc-Barbier et al. 2024).

5 Impact of changes in the 0°C isotherm

5.1 General concepts - definitions

Permafrost is a layer of ground (soil or rock) that remains frozen continuously for at least two consecutive years. It can occur both at the surface and at depth, sometimes extending hundreds of meters below the surface. This frozen ground typically contains ice, sediments, gases, and ancient organic matter. Permafrost is characteristic of polar and subpolar regions, but it also exists in high mountain areas. In Europe, it is found mainly around the Arctic Circle and in the Alps, and to a lesser extent in the Sierra Nevada and the Pyrenees.

Cryosuccion is a phenomenon in which liquid water is drawn, by capillary forces, toward the freezing zone within the rock in order to restore the water film that forms between the ice surface and the pore wall: when a rock cools below 0°C, the water contained in its pores or cracks freezes, but a thin layer of water always remains between the pore wall and the frozen water. As the volume of ice increases, this layer of water shrinks compared to what it would be on a free surface. Cryosuccion refers to the transport of liquid water toward the freezing front. If the increase in pressure caused by cryosuccion exceed the rock tensile strength, it can induce fracturing of the rock mass.

Cryoclasty is the process by which rock is fractured as a result of repeated freeze-thaw cycles.

In a given area, the depth of frost depends on both internal factors (water content, temperature, thermal conductivity, etc.) and external factors (outside temperatures, variations, ranges, frequencies, and snowpack thickness), which strongly influence the geological and climatic dynamics of cold environments. Climate change is leading to a decrease in the number of days with freezing temperatures, which will profoundly alter soil thermal conditions. The average increase in the 0 °C isotherm will reduce the cumulative period during which materials remain frozen. At the same time, this rise in the isotherm may lead to an increase in the number of freeze-thaw cycles that the ground will undergo, since areas that were initially frozen throughout the winter may be subjected to multiple cycles over the same period. This phenomenon is particularly significant in mountainous and polar regions.The change in thermal rhythm is accentuated by a faster melting of the snowpack, which exposes the ground to longer temperature variations. These transformations have several major consequences on the landscape. On the one hand, increased cryoclasty intensifies rock fragmentation, weakening slopes and cliffs (Fig 6). On the other hand, the gradual degradation of permafrost disrupts soil stability, contributing to landslides, subsidence, and the release of trapped gases. Finally, the accelerated melting and retreat of glaciers are profoundly transforming mountain environments, altering hydrology, ecosystems, and natural hazards.



Fig. 6 Photos illustrating slope destabilization related to Permafrost thawing. a. https://thenarwhal.ca; b. Photo K Orlinsky

5.2 Thawing of land that was initially permanently frozen

To understand the issue of ground thawing, it is important to recall the stabilizing role that ice plays in frozen ground: fissural ice acting as a very rigid cement, increases the cohesion and shear strength of rock fractures. Furthermore, it causes the ground to become artificially impermeable, since the water is frozen and cannot flow. Thus, the melting of ice trapped in rock fissures has significant consequences for the stability of rock masses. The temperature increase destabilizes the rock mass through three main mechanisms: increased ice plasticity, loss of adhesion between the ice and the rock, and increased hydraulic pressure within the rock mass due to meltwater. This process is particularly evident in high-mountain areas, where the degradation of permafrost leads to an increase in rockfalls and landslides (Ravanel et al. 2020). During thawing, the melting of ice affects not only the mechanical properties of the bedrock but also its waterproofing function, thereby accelerating cryogenic erosion of surface layers, particularly in the case of weathered rocks (see fig 6a).

Other erosive processes related to ice degradation must be taken into account, particularly paraglacial processes, such as glacial decompression: as glaciers retreat, the release of stress exerted by the ice on rock faces can lead to their destabilization. Ice shelves, which form a band of ice along the coastlines of cold regions, play a dual role. On the one hand, they protect these coastlines from mechanical marine forces, such as waves and currents, thereby slowing erosion. On the other hand, they play an erosive role by promoting abrasion on outcrops, particularly in soft rocks, and by contributing to cryoclasty.

5.3 Impact of freeze/thaw cycles

The impact of freeze-thaw (FT) cycles on rocks is probably the most widely studied climate-related phenomenon both on site and in laboratories. For instance, D'Amato et al. (2014) showed that the frequency of boulder fall on the St Eynard cliff was multiplied by 7 during freeze-thaw episodes.

In laboratories, it is observed that as the number of FT cycle increase, UCS, Elastic Young Modulus, elastic waves velocities and shear properties decrease (Aral et al., 2021; Deprez et al., 2020; Gasc-Barbier and Merrien-Soukatchoff, 2022; Liping et al., 2019; Liu et al., 2020; Ma et al., 2020; Martınez-Martinez et al., 2008; Yavuz, 2011; Zhou et al., 2020 among other)and depending on the experimental conditions, with a sufficient number of cycles, the sample can reach macroscopic failure, which is the illustration of cryoclasty. The physical process behind it lies in the fact that water expands by approximately 9% when it freezes. However, this increase in volume alone cannot explain the damage caused to rocks by freezing. Taber (1930) demonstrated that even when water in soils is replaced by an interstitial fluid that tends to contract, the ground surface still heaves up following freezing. This ‘heaving’ is linked to the cryosuccion described above and has a direct impact on the hydromechanical behaviour of the rock. It leads to the formation of segregation ice (ice lenses) that forms at the freezing front, causing a local increase in volume and a water deficit at depth, which can then result in desiccation fractures. When the ice melts, ice lenses gradually disappear, and in weak or highly fractured rock, this melting causes the rock to deform gradually. This phenomenon is called gelifluxion and macroscopically it looks like creep.

6 Conclusion and outlook

The impact of climate on the stability of rock masses is a complex subject that requires consideration across multiple temporal and spatial scales. In this paper, we have examined three different processes, impact of atmospheric water, positive thermal cycles, changes in the 0°C isotherm, which we have sought to illustrate briefly by describing both field observations and laboratory experiments. Although most of them are clearly identified on field, they are still often poorly described, particularly in terms of constitutive laws. A lot of work remains to be done to be able to accurately model the impact of climate on the rock mass, and even more so if we wish to anticipate the effects of climate change.

7 Acknowledgements

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References

Aires-Barros, L., 1977. Experiments on thermal fatigue of non-igneous rocks. Engineering Geology 11, 227–238.

Al Heib, M., Conil, N., Gombert, P., 2023. Influence of geology and topography on the occurrence of mine massive collapse—back-analysis of a historical collapse of chalk mine (France). Bull EngGeol 82, 230. 10.1007/s10064-023-03234-z

Althaus, E., Friz-T Pfer, A., Lempp, C., Natau, O., 1994. Effects of water on strength and failure mode of coarse-grained granites at 300 C. Rock Mech Rock Eng., 1994, 1994- 01-01; 27(1):1–21.

Alzo'ubi, A.K., Alneasan, M., 2025. The impact of moderate thermal fluctuations on dolomite: From strength enhancement to microstructural sensitivity. Results in Eng. 28, 107679. 10.1016/j.rineng.2025.107679

Aral, İ.F., Boy, R., Dinçer, A.R., 2021. Effects of freeze-thawing cycles on the physical and mechanical properties of basaltic and dolomitic rocks evaluated with a decay function model. Bulletin of Engineering Geology and the Environment 80, 2955–2962. 10.1007/s10064-021-02132-6

Bakun-Mazor, D., Hatzor, Y.H., Glaser, S.D., Carlos Santamarina, J., 2013. Thermally vs. seismically induced block displacements in Masada rock slopes. International Journal of Rock Mechanics and Mining Sciences 61, 196–211. 10.1016/j.ijrmms.2013.03.005

Bernardie, S., Desramaut, N., Malet, J.-P., Maxime, G., Grandjean, G., 2014. Prediction of changes in landslide rates induced by rainfall. Landslides 12. 10.1007/s10346-014-0495-8

Binet, S. et al. 2020. Global warming and acid atmospheric deposition impact on carbonate dissolution and CO2 fluxes in French karst hydrosystems: Evidence from hydrochemical monitoring in recent decades, Geochimica et Cosmochimica Acta, 270, pp. 184–200. 10.1016/J.GCA.2019.11.021.

Breytenbach, I.J., 2022. Seasonal bedrock temperature oscillations and inversions as a function of depth and the implications for thermal fatigue. Physical Geography 43, 401–418. 10.1080/02723646.2020.1847242

Brooks, S.M., Crozier, M.J., Glade, T.W., Anderson, M.G., 2004. Towards Establishing Climatic Thresholds for Slope Instability: Use of a Physically-based Combined Soil Hydrology-slope Stability Model. Pure and applied geophysics 161, 881–905. 10.1007/s00024-003-2477-y

Cascini, L., Cuomo, S., Pastor, M., Sorbino, G., 2010. Modeling of Rainfall-Induced Shallow Landslides of the Flow-Type. journal of geotechnical and geoenvironmental engineering - ASCE 85–98. 10.1061/(ASCE)GT.1943-5606.0000182

Castellanza, R., Lollino, P., Ciantia, M., 2018. A methodological approach to assess the hazard of underground cavities subjected to environmental weathering. Tunnelling and Underground Space Technology 82, 278–292. 10.1016/j.tust.2018.08.041

Cloutier, C., Locat, J., Charbonneau, F., Couture, R., 2015. Understanding the kinematic behavior of the active Gascons rockslide from *in-situ* and satellite monitoring data. Engineering Geology 195, 1–15. 10.1016/j.enggeo.2015.05.017

Collins, B.D., Stock, G.M., 2016. Rockfall triggering by cyclic thermal stressing of exfoliation fractures. Nature Geoscience 9, 395–400. 10.1038/ngeo2686

Conil N., Cosenza P., Defortis S., Do D.P., Gasc M., Jung S., Adi-Aad E. Climate Change and Rock Mechanics – Some Reflections. JNGG 2024. Poitiers, France. June 25-27, 2024.

D'Amato, J., Hantz, D., Guerin, A., Jaboyedoff, M., Baillet, L., Mariscal, A., 2016. Influence of meteorological factors on rockfall occurrence in a middle mountain limestone cliff. Nat. Hazards Earth Syst. Sci. 16, 719–735. 10.5194/nhess-16-719-2016

Delonca, A., Günzburger, Y., Verdel, T., 2014. Statistical correlation between meteorological and rockfall databases. Nat. Hazards Earth Syst. Sci. 14, 1953–1964. 10.5194/nhess-14-1953-2014

Deprez, M., De Kock, T., De Schutter, G., Cnudde, V., 2020. A review on freeze-thaw action and weathering of rocks. Earth-Science Reviews 203, 103143. 10.1016/j.earscirev.2020.103143

Djerbal, L., Melbouci, B., 2012. The Ain El Hammam landslide (Algeria): causes and evolution. Bulletin of Engineering Geology and the Environment 71. 10.1007/s10064-012-0423-x

Eisbacher G. Clague J. 1984. Destructive mass movements in high mountains: hazard and management, Geological Survey of Canada Paper 84-16, Ottawa, Ont. 1984. 230 p. https://publications.gc.ca/site/eng/9.852678/publication.html

Fortin, J., Gasc-barbier, M., Merrien-soukatchoff, V., 2018. Behaviour of rocks in temperature, in: Gasc-Barbier, M., Merrien-Soukatchoff, V., Berest, P. (eds.), Thermomécanique des roches. Presses des Mines, Paris.

Fei, L., Jaboyedoff, M., Derron, M.-H., Choanji, T., Sun, C., 2025. Multiscale observations of diurnal thermal effects on rock failure and crack dynamics in soft marl layers (La Cornalle molasse rock wall, Switzerland). Engineering Geology 354, 108159. https://doi.org/10.1016/j.enggeo.2025.108159

Gasc-Barbier, M., Girma, G., Gendre, V., 2014. Laboratory analysis of thermal fatigue in limestone, in: Rock Engineering and Rock Mechanics: Structures in and on Rock Masses - Proceedings of EUROCK 2014, 10.1201/b16955-46

Gasc-Barbier, M., Merrien-Soukatchoff, V., 2022. Effect of Freezing-Thawing Cycles on the Elastic Waves' Properties of Rocks. Geosciences 12, 103. 10.3390/geosciences12030103

Gasc-Barbier, M., Merrien-Soukatchoff, V., Krzewinski, V., Azemard, P., Genois, J.-L., 2024. Assessment of the influence of natural thermal cycles on dolomitic limestone rock columns: A 10-year monitoring study. Geomorphology 464, 109353. https://doi.org/10.1016/j.geomorph.2024.109353

Gombert, P., 1994. Simplified theoretical approach to karst dissolution. Karst 24:41–51.10.3406/karst.1994.2341

Gombert P, Auvray C, Al Heib M (2013) *In-situ* and laboratory tests to evaluate the impact of water table fluctuations on stability of underground chalk mines. Procedia Earth and Planetary Science 7:304–308

Ghoreychi, M. 1983 Stability of partial workings with pillars in a post-failure state: application to the case of underground chalk quarries. Ph.D. thesis in Vandoeuvre-les-Nancy, INPL 1983

Gómez-Heras, M., Smith, B.J., Fort, R., 2006. Surface temperature differences between minerals in crystalline rocks: Implications for granular disaggregation of granites through thermal fatigue. Geomorphology 78, 236–249. 10.1016/j.geomorph.2005.12.013

Griggs, D.T., 1936. the factor of fatigue in rock exfoliation. The Journal of Geology 44 (7):783-796

Grøneng, G., Christiansen, H., Nilsen, B., Blikra, L, 2011. Meteorological effects on seasonal displacements of the Åknes rockslide, western Norway. Landslides 8, 1–15. 10.1007/s10346-010-0224-x

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). Inter J. of Rock Mech. and Min Sc. 42, 331–349. 10.1016/j.ijrmms.2004.11.003

Hall, K., 1999. The role of thermal stress fatigue in the breakdown of rock in cold regions. Geomorphology 31, 47–63. 10.1016/S0169-555X(99)00072-0

Hall, K., Thorn, C.E., 2014. Thermal fatigue and thermal shock in bedrock: An attempt to unravel the geomorphic processes and products. Geomorphology 206, 1–13. 10.1016/j.geomorph.2013.09.022

IPCC, 2019. Global Warming of 1.5°C IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and the Associated Global Greenhouse Gas Emission Trajectories in the Context of the Climate.

Iverson, R.M., 2000. Landslide triggering by rain infiltration. Water Resources Research 36, 1897–1910.

Korsnes, R.I., Madland, M.V., Austad, T., Haver, S., Røsland, G., 2008. The effects of temperature on the water weakening of chalk by seawater. Journal of Petroleum Science and Engineering 60, 183–193. 10.1016/j.petrol.2007.06.001

Lafrance N, Souley M, Auvray C, Favreau O, Labiouse V (2014) Aging of chalk rocks in an underground quarry. Rock engineering and rock mechanics: structures in and on rock masses: proceedings of the international symposium EUROCK 2014b: 445–450. Leiden: CRC Press

Liping, W., Ning, L., Jilin, Q., Yanzhe, T., Shuanhai, X., 2019. A study on the physical index change and triaxial compression test of intact hard rock subjected to freeze-thaw cycles. Cold Regions Science and Technology 160, 39–47. 10.1016/j.coldregions.2019.01.001

Liu, T., Zhang, C., Cao, P., Zhou, K., 2020. Freeze-thaw damage evolution of fractured rock mass using nuclear magnetic resonance technology. Cold Regions Science and Technology 170, 102951. 10.1016/j.coldregions.2019.102951

Ma, W., Gao, W., Guo, S., Zhao, Y., Wu, Z., Yang, C., 2020. Evaluation and improvement on the freeze-thaw durability performance of the polyurethane stabilized Pisha sandstone for water and soil conservation. Cold Regions Science and Technology 177, 103065. 10.1016/j.coldregions.2020.103065

Martınez-Martinez, J., Benavente, D., Ordonez, S., Garcıa-del-Cura, M.A., 2008. Multivariate statistical techniques for evaluating the effects of brecciated rock fabric on ultrasonic wave propagation.

International Journal of Rock Mechanics and Mining Sciences 45, 609–620. 10.1016/j.ijrmms.2007.07.021

Merrien-Soukatchoff, V., Gasc-Barbier, M., 2023. The Effect of Natural Thermal Cycles on Rock Outcrops: Knowledge and Prospect. Rock Mechanics and Rock Engineering 56, 6797–6822. 10.1007/s00603-023-03420-1

Ollier, C.D., 1963. Sunstroke weathering; examples from central Australia. American Journal of Science 261, 376–381. 10.2475/ajs.261.4.376

Pan, Y., Wu, G., Zhao, Z., He, L., 2020. Analysis of rock slope stability under rainfall conditions considering the water-induced weakening of rock. Computers and Geotechnics 128, 103806.10.1016/j.compgeo.2020.103806

Paquette Y. 2014. Behaviour of the land above partial workings, diagnosis of stability and organisation of the monitoring of abandoned partial workings. The case of the quarries of the Nord-Pas-de-Calais region 42. HAL Id: ineris-00972119. https://ineris.hal.science/ineris-00972119.

Raj, M., Sengupta, A., 2014. Rain-triggered slope failure of the railway embankment at Malda , India Rain-triggered slope failure of the railway embankment at Malda , India. Acta Geotechnica 9, 789–798. 10.1007/s11440-014-0345-9

Ravanel, L., Magnin, F., Deline, P., 2017. Impacts of the 2003 and 2015 summer heatwaves on permafrost-affected rock-walls in the Mont Blanc massif. Science of the Total Environment 609, 132–143. 10.1016/j.scitotenv.2017.07.055

Ravanel L., Magnin F., Gallach X., Deline P. 2020. Évolution des parois rocheuses gelées de haute montagne sous forçage climatique. La Météorologie, 2020, 111, pp.34-40. ff10.37053/lameteorologie-2020-0090ff. ffhal-03028348v2f

Sandersen, F. &Bakkehøi, Steinar&Hestnes, Erik & Lied, K. 1997. The influence of meteorological factors on the initiation of debris flows, rockfalls, rockslides and rockmass stability. Publikasjon - NorgesGeotekniskeInstitutt. 201. 97-114.

Song, Z., Li, X., Lizárraga, J.J., Zhao, L., Buscarnera, G., 2020. Spatially distributed landslide triggering analyses accounting for coupled infiltration and volume change. Landslides v. 10.1007/s10346-020-01451-1

Taber, S., 1930. The Mechanics of Frost Heaving. The Journal of Geology 38, 303–317. https://doi.org/10.1086/623720

Terajima, T., Miyahira, E., Miyajima, H., Ochiai, H., Hattori, K., 2013. How hydrological factors initiate instability in a model sandy slope. Hydrological Processes 28, 5711–5724. 10.1002/hyp.10048

Uwihirwe, J., Hrachowitz, M., Bogaard, T.A., 2020. Landslide precipitation thresholds in Rwanda. Landslides 17, 2469–2481. 10.1007/s10346-020-01457-9

Vargas, E.A., Castro, J.T., Amaral, C., Figueiredo, R.P., 2004. On mechanisms for failures of some rock slopes in Rio de Janeiro, Brazil: thermal fatigue?, *in*: Landslides: Evaluation and Stabilization/Gliss de Terrain: Evaluation et Stabilisation, Set of 2 Volumes. pp. 1007–1011.

Villarraga, C.J., Gasc-Barbier, M., Vaunat, J., Darrozes, J., 2018. The effect of thermal cycles on limestone mechanical degradation. International Journal of Rock Mechanics and Mining Sciences 109. 10.1016/j.ijrmms.2018.06.017

Vlcko, J., Greif, V., Grof, V., Jezny, M., Petro, L., Brcek, M., 2009. Rock displacement and thermal expansion study at historic heritage sites in Slovakia. Circa Geol 58, 1727–1740. 10.1007/s00254-008-1672-7

Wang, J.G., Ichikawa, Y., Leung, C.F., 2003. A constitutive model for rock interfaces and joints. International Journal of Rock Mechanics and Mining Sciences 40, 41–53. 10.1016/S1365-1609(02)00113-2

Yatsu, E., 1988. the nature of weathering: an introduction, Sozosha. ed. Overseas distributor Maruzen Co., Tokyo

Yavuz, H., 2011. Effect of freeze-thaw and thermal shock weathering on the physical and mechanical properties of an andesite stone. Bulletin of Engineering Geology and the Environment 70, 187–192. 10.1007/s10064-010-0302-2

Zhao, X., Sun, Y., Feng, Q., Baharuddin, M.F.T., Hazreek, Z.A.M., Azman, A.A., Hsiao, D.H., Hsieh, C.S., Yeh, L.C., Lin, D.Y., Phan, V.T.-A., 2018. A study on an instability slope in Taiwan subjected to rainfalls. IOP Conf. Series: Earth and Environmental Science 143, 12018. 10.1088/1755-315/143/1/012018

Zhou, X.P., Li, C.Q., Zhou, L.S., 2020. The effect of microstructural evolution on the permeability of sandstone under freeze-thaw cycles. Cold Regions Science and Technology 177, 103119. 10.1016/j.coldregions.2020.103119

Zhou, Z., Cai, X., Cao, W., Li, X., Xiong, C., 2016. Influence of water content on mechanical properties of rock in both saturation and drying processes. Rock Mech Rock Eng 49 (8), 3009–3025.