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Monitoring of Global Warming Effects in High Alps

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Abstract – Global warming is following a particular acute trend in alpine areas, where the recorded temperature increases are larger than on average. This trend has a direct impact on the stability of high mountain slopes, as it provokes the upward receding of permafrost and triggers a series of rockfall events. Although is difficult to pinpoint the direct cause-effect relationship for any recorded event, two general facts emerge: failures are becoming more and more frequent, especially during particularly hot summer seasons; failures tend to concentrate within the altitude range affected by permafrost receding.
In this paper, we discuss the design and installation of the monitoring station at Capanna Margherita hut (Punta Gnifetti 4554m a.s.l., Monte Rosa massif), which is the highest mountain hut in the Alps and in Europe in general.
The design of the monitoring set-up is based on a previous geomechanically survey (by laser scanning and photogrammetry) and numerical simulations performed with the Distinct Element Method. Preliminarily, two boreholes were drilled and BHTV images were recorded to complement geomechanically information. Then two multi-parametric geotechnical monitoring systems (DMS columns) were installed in the boreholes. Considering the climate-driven nature of potential failures, a full set of data is continuously being recorded, including inclinometric, extensometric, piezometric, thermometric and accelerometric data.
Besides focusing on the discussion of the set-up and commenting on the preliminary obtained data, the paper focuses on the logistic and operational challenges related to the installation process at such a high altitude.

Keywords**:** High alps; Rock mechanics; Permafrost; In-situ testing; Monitoring

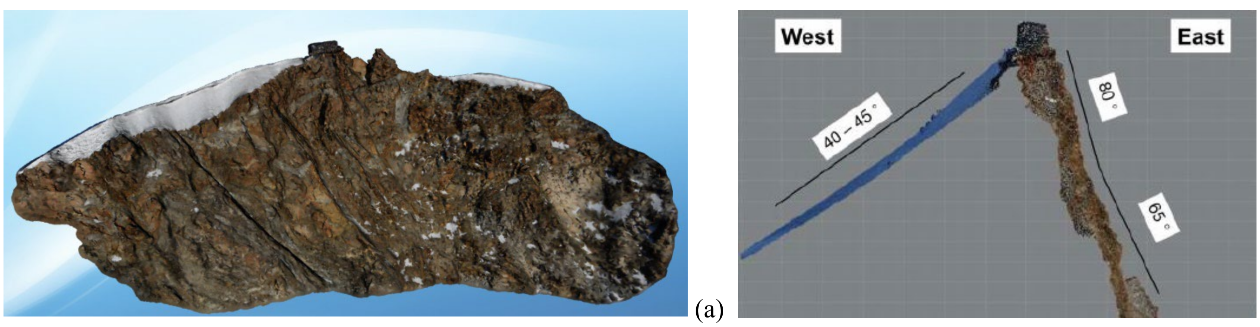
1. Introduction

Air temperature observations in the European Alps, Asia and North America show that warming over recent decades occurred at a rate of 0.3±0.2 °C per decade, which is outpacing the global warming rate of 0.2±0.1 °C per decade [1]. As a consequence, the permafrost distributed either at high latitudes or in alpine areas shows a degradation according to several observations [2]. More specifically, broad evidence of steep rock destabilization by warming permafrost exists and convex topography such as ridges, spurs, and peaks are often subject to faster and deeper thaw than other areas [3]. During the particularly marked heat waves in the summer of 2003 and 2015, a significant number of rockfall incidents were observed in the Alps [4]. These rockfalls occurred in areas influenced by permafrost. According to statistics, among the rockfall events in 2013 and 2015, the temperature of the rock walls ranged from -7.6 °C to 1 °C. Among them, 44% (65 rockfalls) occurred between -1.0 °C and -3.0 °C. Moreover, the analysis of 1389 recent rock slope failures in the Mont Blanc massif also highlighted a correlation with the presence of permafrost at near zero temperature: the occurrence of rock slope failures exhibits a peak in rock faces where the Mean Annual Rock Surface Temperature (MARST) ranges between -2 °C and 0 °C, with 325 incidents (35%) recorded in this temperature range, accounting for 8% of the total rock wall surface area [5].

In this context, it is fundamental to assess the current and future risk scenarios at high altitudes, in particular with reference to sites with structures (typically mountain huts) and infrastructures. This research is in particular devoted to the modelling of the rock mass of Punta Gnifetti-Signalkuppe (Monte Rosa group) and the effects of permafrost degradation on the stability of Capanna Margherita, which belongs to the Italian Alpine Club. Capanna Margherita is located just on top of Punta Gnifetti at 4554 meters a.s.l. and it is the highest hut, and building in general, in Europe (Figure 1).

Figure 1 Capanna Margherita (4554 m a.s.l.)

Research regarding Capanna Margherita started in 2019, due to the concerns coming from unusually high air temperatures (around 10 °C) recorded at the hut. Several in-situ and modelling activities have been performed since then. First of all, an investigation of the geomechanical structure was carried out by means of photogrammetric and laser-scanning methods and the use of ground penetrating radar. This instrumental activity was complemented by direct observations at the rock face below the hut. The reconstructed 3D model of the summit covers about 160 m horizontally and 100 m vertically on the main rock face (Figure 2 (a)). The summit is characterized by a main ridge, which runs approximately along the N-S direction, and two very different slopes on either side of it (Figure 2 (b)). The west side has a relatively moderate slope (40°~45°) and it is covered by a few metres thick layer of snow and ice. The east face (the dip direction is 117° precisely) is characterized by a sub-vertical upper part and a lower part with an inclination of approximately 65°.



(a) (b)

Figure 2 (a) 3D model of Punta Gnifetti; (b) section of the 3D model parallel to the dip direction of the east face.

From data obtained during the survey and literature, the rock mass under the hut is composed of para-gneiss with ortho-gneiss inclusions. Eight main joint sets were detected. However, no information was obtained regarding the possible presence of ice or water in depth.

Starting from this survey, a Distinct Element (DEM) 3D model of the rock mass was then built and used to analyse possible evolutionary scenarios. This model represents the last step of a multiscale research approach where the Distinct Element Method has been used at the scale of materials, joints, and rock mass as a whole [6]. During this research, a large-scale DEM model of the mountain slope was defined and used to reproduce the actual configuration through a back-analysis procedure based on the geomechanical investigation and to assess evolutionary scenarios driven by the increase of joint persistence and temperature [7][8]. Despite incomplete information, the results of the simulations have shown that the numerical model can reproduce the current configuration of the rock face quite well. As to the possible evolution of the rock slope, two external triggering factors, which are considered to be responsible for most real-world collapses, were considered: the increase of joint persistence (which can be caused by repeated cycles of freeze/thaw) and the increase in temperature.

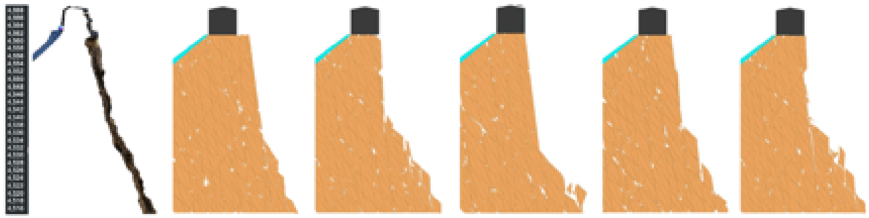


Figure 3 DEM model of Punta Gnifetti; back-analysis for various joint conditions (from [7][8])

Although promising results were obtained, the model is affected by some limitations which are worth further study. For instance, the parametric study was conducted with insufficient data regarding the presence of ice or water in the joints, and with no information about the real in-depth temperature regime. Furthermore, no direct measurements of displacements were available at Capanna Margherita to allow for proper validation.

Considering all these issues, a new and dedicated in-situ investigation campaign has been recently designed and carried out, with the main purpose of getting crucial information about the in-depth structure of the rock mass, temperature, water/ice presence and displacements.

2. In-situ campaign

The activities carried out at Capanna Margherita during the new campaign are first summarised and then individually described in the following. The specific difficulties due to operating at high altitudes are then discussed (see §2.3).

Preliminarily, two boreholes were drilled at Capanna Margherita and BHTV images were recorded to complement geomechanical information (see §2.1).

Then two multi-parametric geotechnical monitoring systems (DMS columns) were installed in the boreholes. Considering the climate-driven nature of potential failures, a full set of data is continuously being recorded by these devices, including inclinometric, extensometric, piezometric, thermometric and accelerometric data (see §2.2).

2.1. Boreholes and BHTV

The first borehole was drilled vertically starting from the access platform to the hut. The vertical borehole reached a 20 m depth. The second one was drilled horizontally on the southeast rock face approximately 5 m below the balcony of the hut overlooking a length of 10 m (Figure 4).

The possibility of performing drilling with core recovery was discarded due to the lack of water at the hut site. Therefore, core destruction drilling with a Down-The-Hole (DTH) hammer was performed. A super-light hydraulic drill was chosen and the operation of the DTH (diameter 90 mm) was guaranteed by two motor compressors transported by helicopter and powered by oxygen during the start-up phase.

During the perforations, no water infill was observed. This information is relevant considering that the activity took place at the end of the warmest period of the year and that minimum air temperatures larger than 0°C were recorded for four consecutive days during the installation. Moreover, no lining was required to keep the boreholes stable, with the exception of the first 2 m of the vertical hole where a PVC tube was installed as a precaution.

The boreholes were then inspected with a BHTV probe which returned the fracture conditions of the rock mass in depth (can be seen in Figure 6). The images will be used for geological analysis and be compared with the surface geomechanical survey carried out by Imageo during the previous research activity at Capanna Margherita (2019-2021).

Figure 4 The vertical and horizontal boreholes position.

2.2. DMS multiparametric columns

DMS (Differential Monitoring of Stability, CSG patent) is a differential multiparametric monitoring system for the stability of soils, rocks and structures. CSG has introduced with the DMS system the “in-place multiparametric in column” monitoring that allows for a complete investigation of the entire borehole and therefore to detect the variations of displacements, temperature, acceleration, etc., offering a large amount of information continuously, simultaneously, and contextually in real-time. Columns are made through the connection of rigid stainless steel tubular elements connected by high-resistance reinforced rubber joints. Sensors and control electronics are contained entirely within the tubular mechanical structure, while the power and data transmission cables are positioned inside the joints to be particularly protected against the external environment. DMS columns can withstand even very high tensile stresses (up to 50 kN), thus allowing monitoring even under severe deformation conditions, as well as extractions and repositioning of the columns over time.

In particular, the vertical hole was equipped with a DMS 2D ROCK column 15 m long, with a measurement step of 1 m (8 inclinometers sensors with range ± 30° and repeatability ± 0.002°; 8 3D accelerometers with resolution 1 mg; 8 temperature sensors with resolution ± 0.1 °C; 2 transducers displacement, resolution 0.01 mm). The horizontal hole was equipped with the combination of the DMS 2D ROCK column and the DMS 3D Plus column thanks to their matchable connection. The incorporation of DMS 3D Plus is introduced because it allows for the measurement of deformation on the longitudinal complementing the monitoring of lateral displacements provided by DMS 2D ROCK.

The DMS system is completed by a control unit that records the data at prescribed intervals and sends them to a dedicated server via a GSM modem.

The interpretation of DMS data is given by a software suite specifically designed for data reading and graphical processing (DMS EW software). The DMS EW software allows to processing of data automatically through differential and cumulative representation of the whole column in terms of north and east components of movements and total displacement (vertical diagrams) and direction (polar diagram). It also allows for analysis of the data time history of all recorded parameters (displacement, velocity, acceleration…) for individual sensors or positions of columns interested in specific kinematics.

2.3. Installation issues

Due to its unique location and environment, the installation had to face numerous challenges. The main difficulties arose from environmental factors such as low temperatures, oxygen deficiency, reduced air density, and wind gusts, as well as the morphological context, including limited spaces for helicopter operations and highly exposed steep rock walls where workers had to operate. Furthermore, the on-site activities at Capanna Margherita had to take place in September, after the closure of the refuge so that the normal activity of the hut was not disrupted. This left just a limited time window and the work had to be completed in the shortest time possible, taking advantage of good weather conditions and relatively warm conditions (for the altitude) before winter.

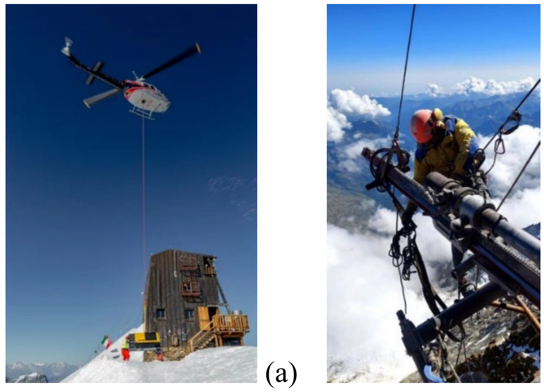

(a) (b)

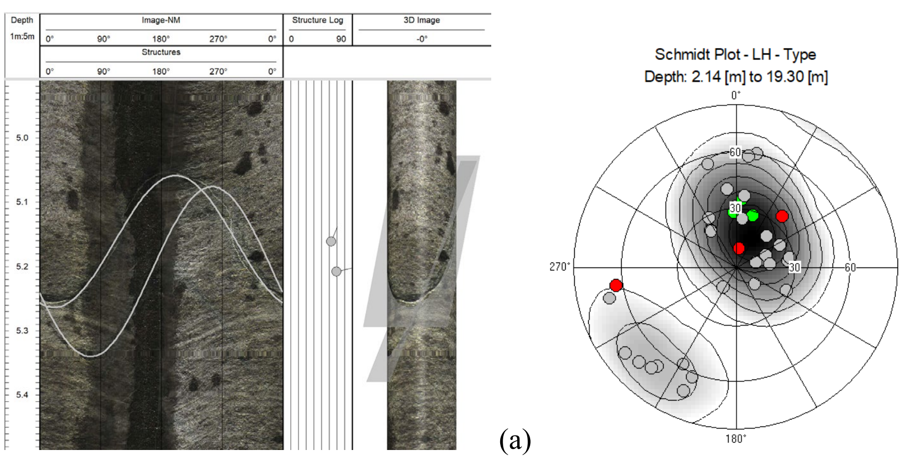
Figure 5 (a) compressor transported by helicopter; (b) perforation at the east face.

3. Data analysis

The images obtained from BHTV will be mainly used for updating the geomechanical information available from previous research. Data monitored by DMS has been recorded since October 10, 2023. While long-term data holds greater significance against a backdrop of rising temperatures, the five months of data currently recorded are worthy of analysis and may yield preliminary findings.

3.1. Rock structure (BHTV)

When a perfect plane crosses a borehole, and the inner borehole surface is projected onto a plane, the resulting intersection lines are sinusoidal (or linear if the plane is perpendicular to the borehole). Therefore, the sinusoidal curves observed on the obtained BHTV images can be analysed to determine the dip and dip direction of joints, given the diameter and direction of the borehole. However, unlike the perfect plane scenario, the intersection shapes between joints and the borehole are not perfect and a specific image interpretation software is required. This tool allows us to reconstruct in 3D the virtual core of the borehole and visualize the joints. An example of the interpreted BHTV data is shown in Figure 6 (a). The dip and dip direction of all joints analysed in the vertical BHTV images are summarized in Figure 6 (b). The same analysis has also been applied to the horizontal BHTV images.



(a) (b)

Figure 6 (a) Geomechanical analysis based on BHTV; (b) Schmidt Plot of joints recorded in the vertical borehole.

3.2. Temperature

Each modulus is equipped with temperature sensors and the temperature is recorded continuously. In the vertical column, 15 sensors are distributed with 1 meter step. Figure 7 shows the temperature recorded in the vertical column on the 10th of each month over the past five months (October 2023 to March 2024). It can be observed that in October 2023, temperatures near the surface are slightly higher than those at deeper levels, hovering around -2.0 °C. However, it can be noted that November witnessed a sudden drop in temperatures, resulting in a significant decrease in surface temperatures while deeper temperatures remained largely unchanged. As temperatures continued to decline, a trend emerged where temperatures increased with depth. From November 2023 to March 2024, there was a greater temperature gradient near the surface, although this phenomenon became less pronounced over time. Figure 8 shows the temperature recorded in the horizontal column. The top of the borehole refers to the side near the exposed rock surface (the dip direction is 117° precisely), whereas the point 8 meters from the left is at the end underneath the hut, close to the ice cover of the west mountain slope. In October 2023, temperatures at the rock face were much larger than at depth. It is noteworthy that temperatures within approximately a 2-meter range from the exposed rock surface are above 0 °C at this point. Similarly to what was observed in the vertical column, a sharp temperature drop occurred in November 2023, leading to a significant reduction in temperature on the side near the exposed rock surface, persisting until January 2024 and affecting temperatures at all depths. In February, temperatures near the surface experienced a slight rebound. Furthermore, temperatures on the side covered by ice consistently decreased over the five-month period. It is evident that temperatures closer to the West slope are more stable and consistently lower than those on the east (the exposed rock surface).

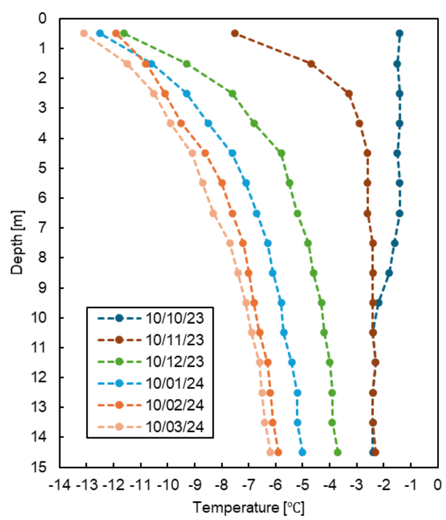


Figure 7 Temperature along the vertical borehole.

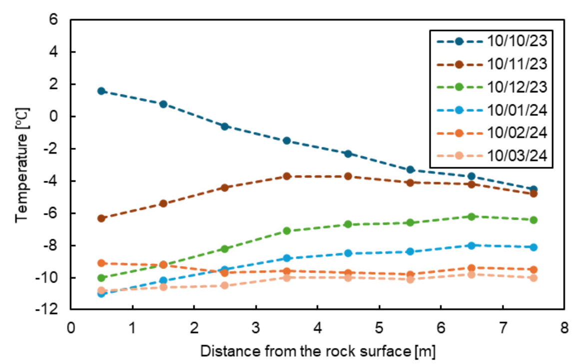


Figure 8 Temperature along the horizontal borehole.

To further analyze the temperature trend at either end of the vertical and horizontal columns, Figure 9 shows the daily average temperatures starting from October 10, 2023. Module 0 of the horizontal column corresponds to the sensor close to the West side, while module 7 corresponds to the East rock face. Module 0 of the vertical column corresponds to the sensor at the bottom while module 14 corresponds to the one at the top top. The daily minimum and maximum air temperatures are also shown in Figure 9. It is easily observed that the temperatures close to the surface (module 7 and module 14) are significantly influenced by air temperature, exhibiting noticeable fluctuations. The temperature near the exposed rock is often higher than the maximum air temperature for most of the time, which is due to the influence of solar radiation. This point will be discussed later. In contrast, the temperature trends in depth are much smoother, as expected.

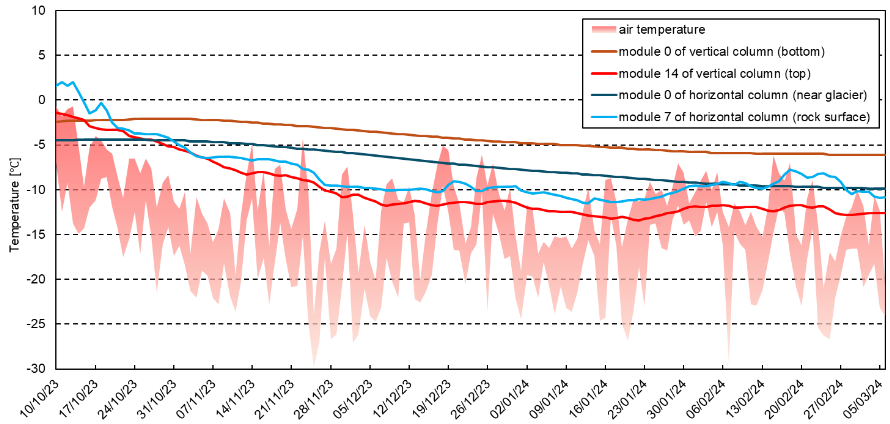


Figure 9 Air temperature and daily average temperature in boreholes.

To better illustrate the impact of weather on the temperature of the exposed rock surface, Figure 10 presents temperature recordings taken every half hour in module 7 of the horizontal column. Daily oscillations are quite evident until October 19th, with the maximum temperature typically recorded at 3 p.m. and the minimum one around 9 a.m. However, oscillations became less pronounced and eventually disappeared after October 19th, when a snowfall occurred (Figure 11). Although there is no direct verification, at the moment, it seems reasonable to assume that the snow cover maybe protecting the rock face from direct solar radiation.

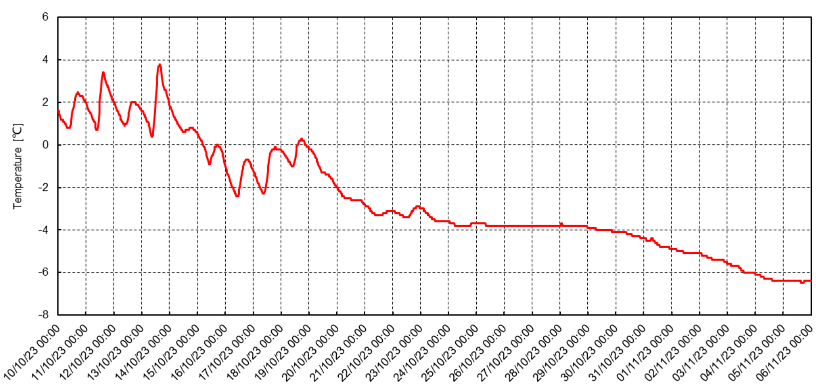


Figure 10 Temperature at the rock face (module 7 of horizontal column).

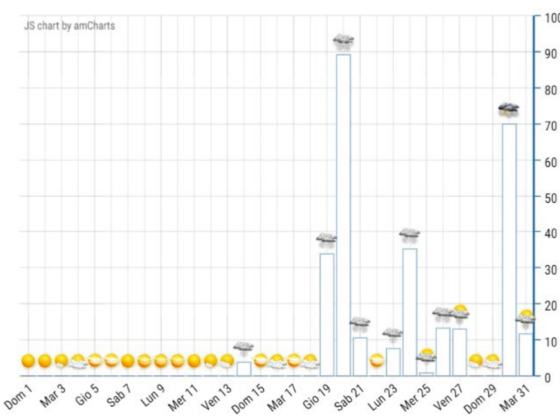


Figure 11 Precipitation in October 2023.

4. Perspectives and conclusions

Observation at Capanna Margherita is planned to continue for at least three years. Seasonal temperature variations as well as annual temperature changes render this project more meaningful over an extended period. However, based on the installation of equipment and the data recorded over the past five months, some preliminary conclusions can be drawn.

BHTV was employed for geological analysis, enhancing the understanding of the rock mass structure. From the temperature data recorded over the past five months, it is evident that surface temperatures are influenced by weather conditions, while temperature variations at a depth of 15 meters are more gradual. In particular, temperatures near the exposed rock surface are significantly affected by weather, exhibiting pronounced daily oscillations before consecutive snowfall, while temperatures near the snow-covered side exhibit gentler variations. Notably, temperatures at the exposed rock surface exceeded 0°C at the onset of observations. A meaningful correlation between displacements and temperature will require a longer observation period, including the warmest season. At the same time, the numerical model will be updated with new information, and it will be used for more realistic predictions.

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