Rock mechanics and engineering for the Klein Matterhorn glacier paradise (Zermatt, Switzerland)

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Abstract. The Alpin X project is carried out by the Zermatt Bergbahnen AG and aims at establishing a touristic link between Zermatt in Switzerland and Cervinia in Italy while facilitating access to the top of the Klein Matterhorn. This very challenging project is based on the construction of two new modern cableways joining each other at adjacent arrival stations founded in the 50–70° steep west face of the Klein Matterhorn, at 3'820.5 m a.s.l. Due to the steepness of the slope, construction works require extensive excavation and stabilization of the serpentinite bedrock and consequently to address various problematics related to superficial and shallow rock instabilities inside and outside the construction area. Moreover, the predominance of permafrost conditions required to adapt the techniques for the execution. While the first cableway from the north-side has been operational since winter 2018/2019, the second from the south is still under construction and will open in winter 2021/2022.

1. Introduction

The high-altitude ski domain Matterhorn Paradise (Mattartal, Switzerland) spreads over 2200 m elevation from Zermatt at the bottom of the valley to the top of Klein Matterhorn at 3883 m a.s.l. (see figure 1). Since 1979 a double cabin cable-car provides an easy access to the summit for skiers, mountaineers and pedestrians throughout the entire year, making this place the highest point accessible by cable-car in the Alps. This unrivalled situation has led to a continuously growing number of visitors. In order to guarantee a touristic link with Italy and to increase transport capacity, the project Alpin Crossing\textsuperscript{[1]}, referred as Alpin X in the following, was initiated and the construction of two additional modern cableways, starting on both north and southeast sides of the Klein Matterhorn and joining on the summit area, was decided by the Zermatt Bergbahnen AG. Due to the limited space available on the summit ridge of the Klein Matterhorn, the locations of the two adjacent new arrival stations were chosen in the 50-70 degree steep west face, at the exit of an existing gallery at 3'821 m a.s.l. in (figure 1). At this location, the slope inclination made it necessary to carry out substantial multi-level excavations for the foundations of the envisioned buildings, leading to the setting up of a completely new rock geometry composed of several walls and terraces. In this context, geological and technical preliminary studies for the foundation of the two arrival stations were performed and results pointed out the need of perennial rock stabilization measures combined with a suitable excavation process, in order to protect the workers and facilities against rock instabilities during both the construction- and operation.
This paper gives an overview of the challenging excavation works carried out for the construction of the two new arrival station on the Klein Matterhorn, with a focus on the rock stabilisation and protective measures set up for both the construction and operation periods. First of all, the high-altitude site of the Klein Matterhorn is presented, and the characteristics of the Alpin X project are then briefly described. Second, a geological background of the area as well as an overview of the rock instability to be considered during the construction time and in the final state are given. Finally, the excavation process is detailed and the rock stabilisation concept as well as the long-term monitoring system are described.

Figure 1. (a) Location of the Klein Matterhorn, close to the village of Zermatt (Walliser Alpen, Switzerland) Source: adapted from Swisstopo; (b) Routes of the two new cableways; (c) Situation of the two new arrival stations in the west face of the Klein Matterhorn, as planned at the end of the construction works.

2. Context of the project

2.1. Situation of the Klein Matterhorn and climatic conditions

The Klein Matterhorn is located in the Swiss canton of Valais, on the municipality of Zermatt. This four-sided pyramidal peak culminates at 3’883 m a.s.l and is stretched along the North-South direction with two predominant, ice-free faces oriented to the west and east (see figure 1). The summit area is less than 2 km away from the Italian border and about 9 and 7 km from the villages of Zermatt and Cervinia.

Due to its high elevation, the construction site is subject to very harsh climatic conditions with the predominance of winter conditions from October to June and generally very important day/night air temperature gradients. Air temperature are most of the time negative and show minimum values around -30°C and maximum values that can exceed 5°C during the July-September period (see the annual temperature distribution for the year 2015 in the figure 2). According to the terrain orientation, these values can however show substantial variations.

Snowfalls are expected all year around on the Klein Matterhorn, but the snow episodes leading to the most important accumulations occur generally between March and June. At this time, snowdrifts of several meters can be locally reached under the effect of the wind. Due to raising air temperatures and increase in sunshine, melting period starts in Mai-June and results in a rapid withdrawal of the snow cover in the west face, together with significant water flows at the surface. Because of its central position on the main ridge of the Alps, the summit area is directly exposed in case of foehn episodes, resulting in wind gusts that can exceed 150 km per hour.
2.2. The Alpin X project

The Alpin X (X for Crossing) project is carried out by the Zermatt Bergbahnen AG. It aims at providing a pedestrian connection between Zermatt in Switzerland and Cervinia in Italy while facilitating access to the top of the Klein Matterhorn. It is based on the construction of two new generation 3S cableways, one starting from Trockener Steg in the north (hereafter referred to as n°1) and the other from Testa Grigia in the south (hereafter referred to as n°2), both joining up in the west face of the Klein Matterhorn (see figure 1b). The construction of the cableway n°1 was carried out between 2016 and 2018 and since then has been operational 365 days a year, whereas the construction works of the cableway n°2 started in 2019 and are still in progress. The opening is planned for winter 2021/2022.

Many companies were commissioned by the Zermatt Bergbahnen AG to take part in the project, in particular: the construction companies Imboden AG and Cogeis SPA for the construction works, Leitner Ropeways which designed and produced the cableways, the engineering office LABAG, which was in charge of the static calculations of the stations and their foundations; the company GASSER Felstechnick, which performed the rock stabilization and excavation works; the company Huggenberger, which provided the instruments dedicated to the long term rock monitoring and the geology office Geotest, which was in charge of the geological aspects and natural hazards related expertise.

3. Geological background and local rock temperatures conditions

The summit area of Klein Matterhorn is formed by the Ophiolite Zone Zermatt – Saas Fee, the remains of an ancient ocean floor, composed of serpentinite. The rock is affected by a strong foliation k3, dip-slope oriented and 50-70° steep, that intersects a secondary ENE-WSW system of sub-vertical discontinuities k1 (see figures 3 and 4a). In the south half of the west flank, the rock-face is cross-cut over the entire height by two 40 m spaced and 5 m wide, steep ravines. These correspond to two steep east-west oriented shear zones k2 and k4 that crosscut the entire mountain peak.

At the surface, the combination of the k1 and k3 discontinuities leads generally to a highly undulated terrain composed of loose rock slabs of up to a depth of 1-2 m. Locally, bigger rock flakes with volume of up to several tens of m³ are also found (see figures 4 and 5). The superficial alteration of the serpentinite is significantly enhanced in the vicinity of the two shear zones. On the contrary, the underlying rock from 2 m depth is composed of compact serpentinite characterized by a better stability. The existing discontinuities are generally closed inside the mountain (see figure 6). Note that the two neighboring arrival stations are located on both sides of the central gully resulting from the shear zone k2.
Figure 3. (a) Overview of the west face before the beginning of the construction works, with the above-mentioned shear-zones (red pointed line) and the perimeter of the two arrival stations: (b) Diagram showing the main discontinuities affecting the serpentinite.

Figure 4. (a) Strongly foliated serpentinite at the excavation front. (b) Typical superficial undulated rock flakes.

Figure 5. Superficial blocks with volume reaching several tens of m³, secured (a) and planned to be purged (b).
Figure 6. (a) Deep rock layers exposed in the already existing central tunnel and (b) at the blasting front of the new connecting tunnel (see the location in figure 8).

Due to the high altitude of the construction area, predominant permafrost conditions have to be considered within the rocky massif. This results in continuously negative rock temperature from a depth of about 2 m, while rock temperatures in the shallow layers are affected by strong seasonal variations and become positive in summer, forming the so-called active zone (see for instance in figure 7). This rock temperature configuration leads to the existence of small extent ice fillings inside the foliation or cracks of the shallow and superficial layers (see figure 7), some of them thawing and draining at the beginning of the melt season around the mid-June. The extent of the permafrost body within the Klein Matterhorn tends to diminish due to both climate warming and local anthropic activities related to existing facilities and constructions works. This results in a progressive thickening of the active layer coupled with an increase in the occurrence of rock instabilities in the superficial layers during the melt season.

Figure 7. (a) Internal rock temperatures measured within a borehole at various depths. The variations observed in 2015 close to the surface are partly due to the beginning of the construction works. Source: Lorenz King, University of Giessen. (b) Ice filling within the foliation at the excavation front.
4. Characteristics of the rock excavation

The rock excavation extends over a length of 65 m, a maximum width of 45 m and exhibits in the final state a maximal elevation difference of about 50 m for a total volume of about 10'000 m$^3$. It is designed in order to allow the direct connection between the two arrival stations and is organized around a main level at 3'820.5 m, at which passengers of both cableways drop-off and can access the already existing central tunnel (see figure 7a-b). This reference level is surrounded by a 20 m high wall, at the top of which the roofs of the stations are founded. Downwards, the excavation is spread over several steps separated with vertical walls up to 10 m high. While the roof of the arrival station 1 is placed on a L-shaped concrete base, excavated in the rock, the roof of the station 2 lays on a concrete structure anchored in the surrounding rock-wall (see figure 7c). The connection of the two stations with the central tunnel is realized with two secondary tunnels. The first one was drilled before the construction works while the second has been excavated during the construction works.

![Figure 8](image)

**Figure 8.** (a) Situation of the excavations of the arrival stations 1 and 2. The significant gully k2 is clearly visible in between. (b) 3D Overview of the excavation 1. (c) 2D profile across the excavation 2. The anchors for the rock stabilisation are shown in black. The position of the borehole extensometers and thermistors, installed for the monitoring of the rock stability, are indicated with the green points and lines.
5. Expected rock instability and damage potentials

5.1. Superficial and shallow rock instabilities

The combination of the local geology with the predominance of regressing shallow permafrost and enhanced freeze-thaw effects results in recurrent spontaneous superficial rockfalls, with volume up to 1 m$^3$. Such instabilities, already pre-existing in the whole west face, is then particularly enhanced in the newly excavated vertical rock walls surrounding and separating the different levels of the excavation. More occasionally, bigger rock blocs with volume of several tenths of m$^3$ and laying on the 50-70° steep slope upwards from the excavation might be destabilized due to the disappearance of the ice “cementing” them to the ground. This type of hazards is encountered more particularly in the southern part of the face, on both sides of the shear zone k2 (see figure 5a). In the absence of protective measures, these rock instabilities directly endanger people and facilities during both the construction time and the operation period.

5.2. Deep-seated instabilities

In the deeper rock layers, the overall compact character of the rock coupled with the absence of open discontinuities, renders the occurrence of spontaneous large-extent instabilities unlikely to happen in a short-term period. However, and although large extent ice bodies are absent within the massif, a progressive evolution towards instable rock configuration cannot be fully excluded on the long term in the context of regressing permafrost. Moreover, although the net weight balance of excavated rock and added reinforced concrete construction elements is negative, the exposure of deep-seated rock volumes to surface conditions will result in a rearrangement of the temperature-strain regime in the rock.

6. Protection and rock stabilization concept

6.1. Description of the concept

The following integral protection concept was designed in order to ensure the safety and long-term stability in the whole construction site and then to protect the newly built stations as well as the people moving inside:

- First, 4 rows of dynamic rock-fall protective nets as well as stabilizing meshes bolted on the rock-surface were installed over the entire width of the slope between the top of the envisioned excavation and the summit ridge as a means for preliminary protection of the whole construction site. Locally, the biggest blocs at the surface with large volumes were directly anchored in the ground (see figure 7).

- Subsequently the excavation works could be started. In a first phase, the upper 20 m rockwall was cut from the top, with several intermediate berms. The rock was generally excavated with explosives or, to a lesser extent, by means of mechanical excavators. Consecutive substeps of max. 2 m height were considered, for practical reasons and also in order to reduce the volume of potential instabilities. The stability of the newly excavated serpentinite was regularly assessed by the geologist, and a systematic anchor grid was set up, allowing to entirely cover the wall once this phase was terminated. In a second phase, the lower levels below 3’820.5 m a.s.l were cut following the same procedure.

6.2. Technical adaptations for the execution

Provided the existing permafrost conditions of the rock on one hand and the need to preserve it in order to limit the initiation of superficial rock instabilities on the second hand, the techniques used for the execution of the excavation and drilling works had to be adapted. In particular, a specific mortar combined with pre-heated water was used to fix the anchors of the protective measures, allowing reliable sealing with borehole temperatures as low as -4°C. In order to limit the heat inputs, all drillings were performed without addition of water, whilst injection socks were used in boreholes that encountered open cracks in order to reduce potential cement leakages.
7. Rock monitoring concept
In order to detect the initiation of rock instabilities in the deep rock layers below and behind the stations, the evolution of the displacements on both sides of deep crossing discontinuities as well as potential warming of the internal rock temperatures are monitored by means of 4 triple borehole extensometers composed of 1 m long steel rods (E1-E4) and 4 triple borehole Thermistors (TH1-TH4) (see respective locations in figure 7). These instruments were installed in 10° downwards inclined boreholes drilled in the lowest levels of the excavation platform as well as directly below the support areas of the roofs (see figure 9a). They provide measurements at 3 distinct depths between 5 et 30 m. Until now, no significative displacements have been detected, whilst internal rock temperatures are still below 0°C but are affected by a slight warming. It has also to be noticed that additional clues regarding changes in the state of stress within the rock can also be deduced from measurements of the internal stress of the pre-stressed anchors placed in the foundations of the two stations (see figure 9b).

![Figure 9](image)

**Figure 9.** (a) Installation of the borehole extensometers. (b) Setting-up of the pre-stressed anchors.

8. Conclusion
As part of the visionary project Alpin X, the construction of 2 new arrival stations in the west face of the Klein Matterhorn is a unique technical challenge, for both the foundations and construction works and subsequently for the very demanding set-up of the cableway elements. Due to the enhanced alteration at the surface of the serpentinite, systematic stabilization measures had to be set up in order to integrally secure the construction site and the newly build stations against rockfalls. Moreover, excavation and drillings techniques were adapted with respect to the predominant permafrost conditions. On the long term, the initiation of potential instabilities within the deep rock layers below and behind the stations is monitored by means of various sensors.

References
[1] Alpin X Project, Zermatt Bergbahnen AG, Zermatt, Switzerland