Siegener Symposium "Geomesstechnik" 2023

Geotechnique Monitoring for Alpine Infrastructure in Permafrost Conditions

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1. Introduction:
The stability of infrastructure in the Alps, such as cable car stations and supports, avalanche barriers, railway installations and military defense structures, is endangered by thawing permafrost. The safety of transport facilities such as roads, railway lines, dams and reservoirs can be severely compromised by gravitational rockfalls and ground movements, which are also triggered by thawing permafrost. The successful realization and maintenance of a structure in areas with permafrost represents a technical and financial challenge for the clients and planners involved.
When planning a structure, special load cases and hazard patterns must be taken into account, which also have to take into account potential changes in the permafrost subsoil. By recording the relevant parameters in the subsoil, risks influenced by permafrost changes can be recognized and monitored in order to improve safety as part of an early warning system and of structural health monitoring.

2. Some specific terms and phenomena in connection with structures stability
Freeze-up Elevation and ejection of objects (e.g. foundations) In the subsoil due to frost action.
Thaw-induced loosening The reduction of the bearing density and thus the compressive and shear strength when a permafrost soil thaws.
Thaw-induced consolidation A time-dependent compaction of the subsoil (increase in bearing density) provoked by melting and drainage of excess pore water.
Thaw-induced sliding Slope instability provoked by thawing ground ice.
Frost heave Upward or lateral movement of the subsoil or of objects located in / on the subsoil caused by ice formation.
Frost splitting/blasting Mechanical destruction of rock caused by pressure, which occurs when water freezes in rock discontinuities.
Uplift pressure Upward pressure generated by the freezing of the subsoil. The uplift pressure is responsible for the uplift of infrastructures.
Permafrost degradation A decrease in the thickness or distribution of permafrost.
Permafrost-preserving construction methods Construction methods that enable the preservation of permafrost.

Permafrost is frozen ground material that has negative temperatures throughout the year. The layer of soil between the ground surface and the permafrost level is the thaw layer (Fig. 1), which thaws in summer and freezes in winter. The permafrost level is the upper limit of the permafrost body

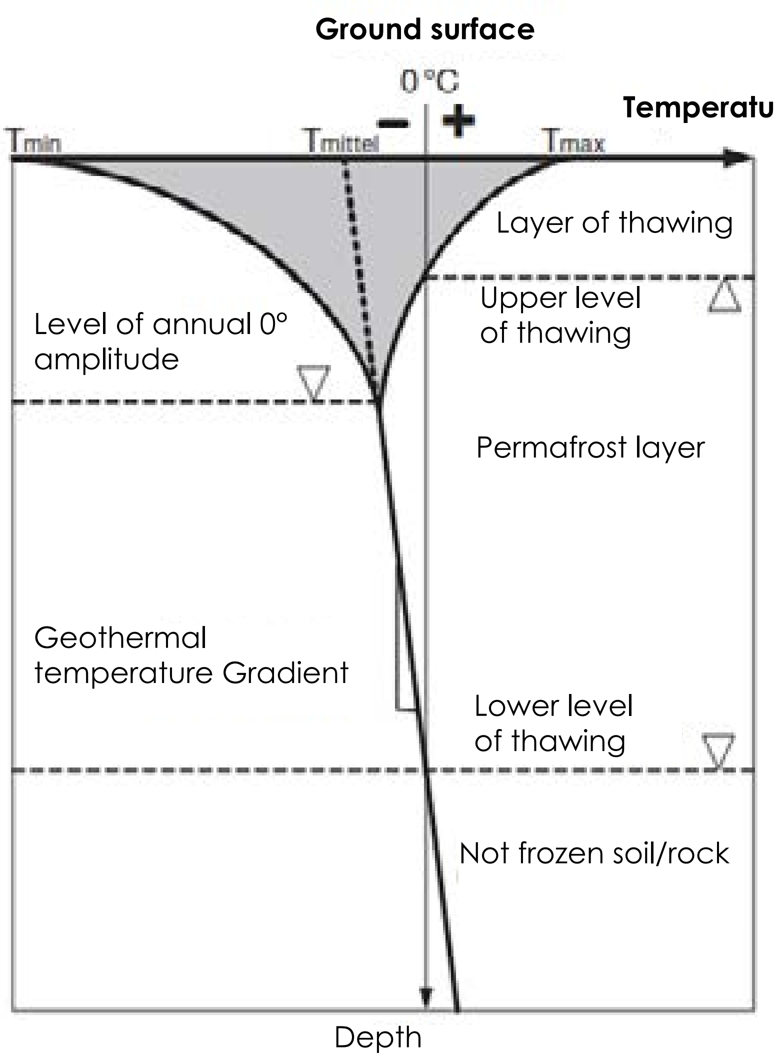
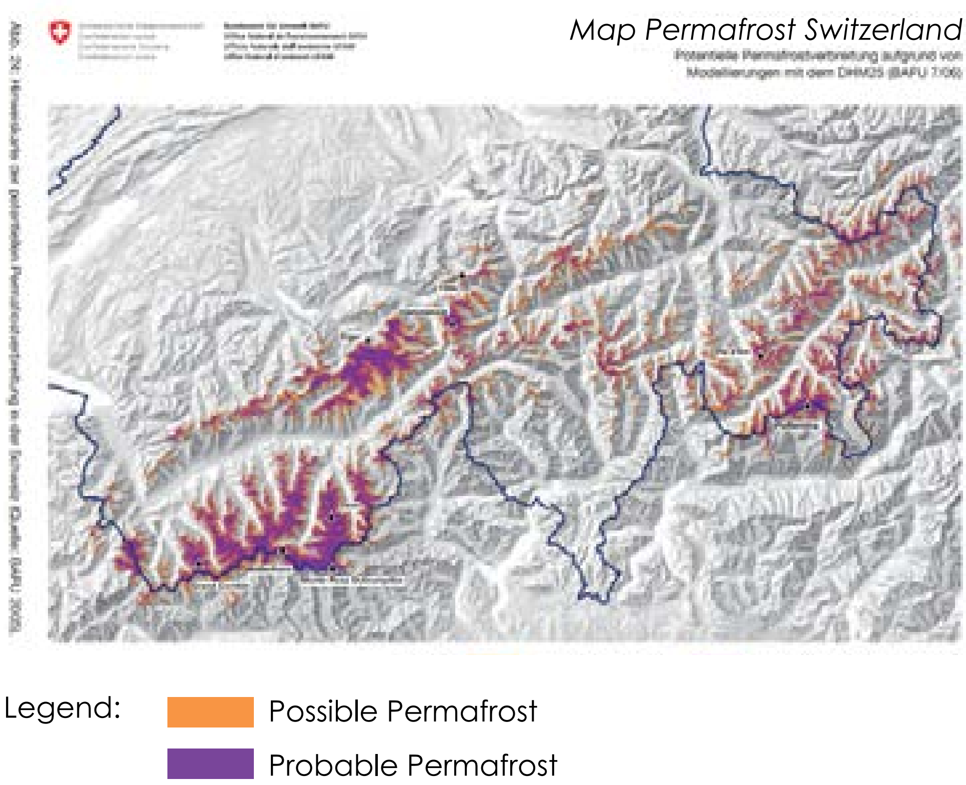
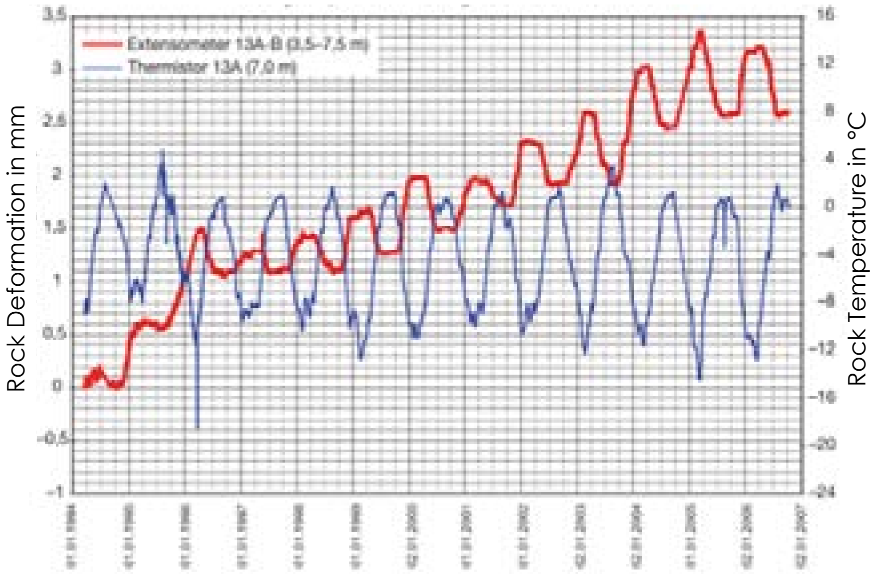


Fig.1: Important terms and typical temperature distribution (black curves) in a permafrost soil. The grey area shows the range of seasonal temperature fluctuations in the subsurface.
In the Alps, permafrost can occur from an altitude of approx. 2000 meters above sea level. This altitude can vary greatly depending on exposure and slope position. In Switzerland, an area of approx. 6% is covered by permafrost.



The snow cover, air temperature, radiation and topography, but also the soil conditions (thermal properties) and local hydrogeology have a strong influence on the development of permafrost. The geotechnical properties, primarily the strength and deformation behavior, of a subsoil are strongly influenced by permafrost. The mechanical properties of solid rock (e.g. a rock face, rock slope) in permafrost are primarily influenced by weathering caused by frost (frost blasting) and the stability of the rock structure supported by frost.

Jungfraujoch, Sphinx, Rock temperature and Rock Deformation 1994 to 2006



3. measurement and monitoring concept for geotechnical structures in permafrost
Based on a risk assessment with field investigations, possibly supported by laboratory tests for planned and existing buildings and the survey or planning of the site and the supporting structure, parameters are determined which are used for a monitoring concept. A monitoring plan for new and existing buildings documents the monitoring and measurements to be carried out and defines the measures to be derived from them. The following methods are used for the preliminary investigation of the permafrost occurrence:

- Ground surface temperature or base temperature of the snow cover is a simple and efficient method of obtaining information on the spatial distribution of permafrost
- A solar compass is used to determine the potential duration of solar radiation for each month at any point in the terrain.
- Terrestrial surveys can be used to determine any creep movements and their velocities, as well as subsidence, uplift and volume changes on rock and soil surfaces and on existing structures.
- Geophysical measurement methods such as geoelectrics, georadar or seismics make it possible to determine the temperature, water and ice content of the ground, as well as the stratigraphy.

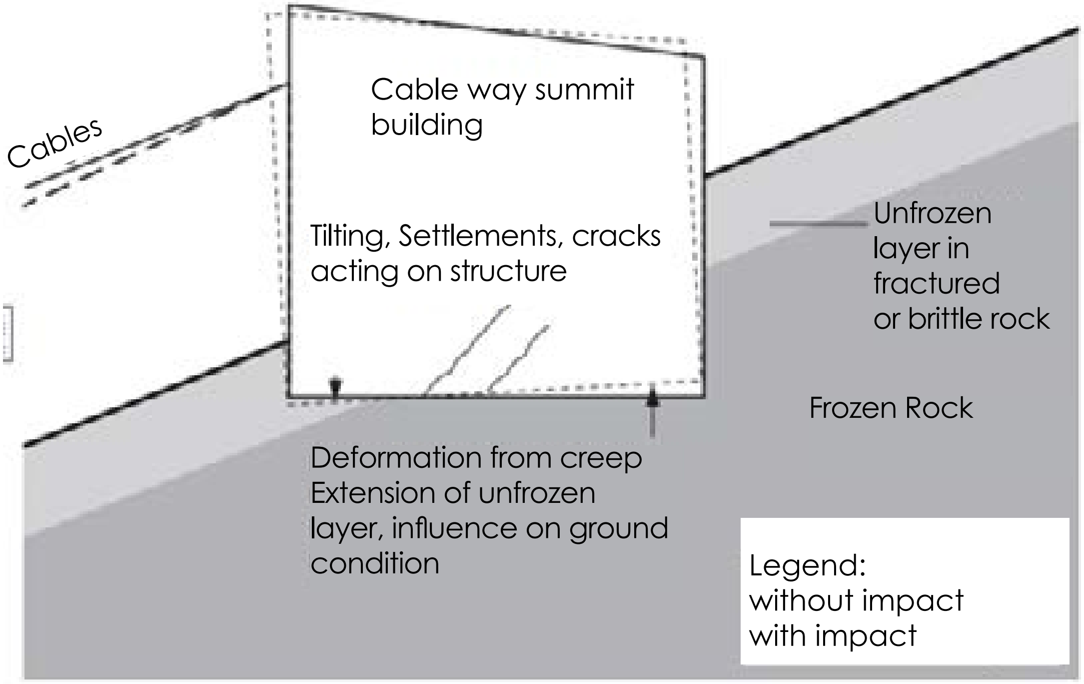
Permafrost can be detected using the following methods:

- Drilling of exploration boreholes offer the possibility of obtaining direct information about the properties of the subsoil in the uppermost meters and it is possible to install measuring instruments such as thermometers in the ground. If carried out carefully the permafrost can be observed directly in the drill cores of the borehole.
- Boreholes provide direct information about the properties of the subsoil down to a great depth. The thawing layer should always be drilled through and, if possible, the base of the permafrost body should be reached. In all cases, drilling with water should be avoided in order to disturb the permafrost as little as possible. Instead of water, air should be used to flush the borehole. To enable subsequent measurements, the boreholes are fitted with a watertight pipe.

The pipe should be grouted in and protected with a man hole (with cover) on the surface. For deformation measurements (inclinometer and/or extensometer measurements), the boreholes are equipped with inclinometer and probe extensometer tubes, e.g. Magnet-Extensometer, T-Rex or Sliding Deformeter, and the annular space between the measuring tube and the ground is grouted.

In boreholes various measurements can be taken to record the condition of the subsoil and any changes in the permafrost.
- Temperature measuring strings operated with a data logger are used to record the extent and position of the permafrost body over time and precisely measure its temperatures.

Schematic drawing of a cable way summit station partially in permafrost foundation



Preparation of the monitoring system
Monitoring with measuring systems is ideally carried out before construction begins. Systematic planning of measurements and monitoring is based on a risk assessment that includes the following elements:
- Risk identification
- Risk assessment
- Risk influence (minimization) through monitoring measurements

Optimized monitoring of the subsoil and structure begins with systematic planning of the measurement systems and their operation:
a) Problem definition, questions that need to be answered or dealt with
b) Which physical parameters are to be recorded in meters, °C, Newtons, Pascals, time, and in what magnitude and accuracy
c) What measurement principle (point-by-point, line-by-line, spatial) is applied
d) Which measuring systems are to be used (technical suitability, costs, availability, robustness, interchangeability of measuring system for long measuring periods, redundancy)
e) Measurement program (period, measurement frequency, limit and alarm value handling, presentation of data and interface to users)
f) Data evaluation and information processing (responsibility),
g) Measures in normal operation and in the event of an incident (e.g. if limit values are exceeded, information flow, etc.)

Measurements such as temperature and deformation measurements that start early, i.e. long enough before construction begins, if possible several years in advance, may reveal changes caused by the construction work.
If damage to the structure can occur even with small deformations, precise and sensitive measuring systems must be used to draw meaningful conclusions.

Monitoring systems during execution

The following summary lists various monitoring systems and methods:

a) Visual monitoring Visibility Daily, Weekly
- Cracks, cavities
- Ice
- Changes in general

b) Automatic ground / air temperature measurements Accessibility Hourly Daily
- Temperature development on surfaces, in boreholes and on supporting structures

c) Geodetic surveying
- Displacements on the ground surface and on structures Continuous Weekly / Monthly

d) 3D laser scanning
- displacements of the terrain
- Large volume changes in the terrain(e.g. due to rock movements, ice shrinkage, ice formation, etc.)
- Displacements of infrastructures Measured reference points in the terrain

e) Borehole probe extensometer measurements (e.g. Magnet-Extensometers, T-Rex, Sliding Deformeter, DEX)
- Differential heave settlements in the subsoil (displacement profiles along the borehole)

f) Borehole inclinometer measurements
- Horizontal displacements in the subsoil Inclinometer tube in borehole
- Monthly automatic measurement with inclinometer measuring chain during critical construction phases

g) Extensometer measurements Accessibility Daily - Weekly, during critical construction phases automatic measurement
- Displacements of rock fissures
- Displacements of buildings

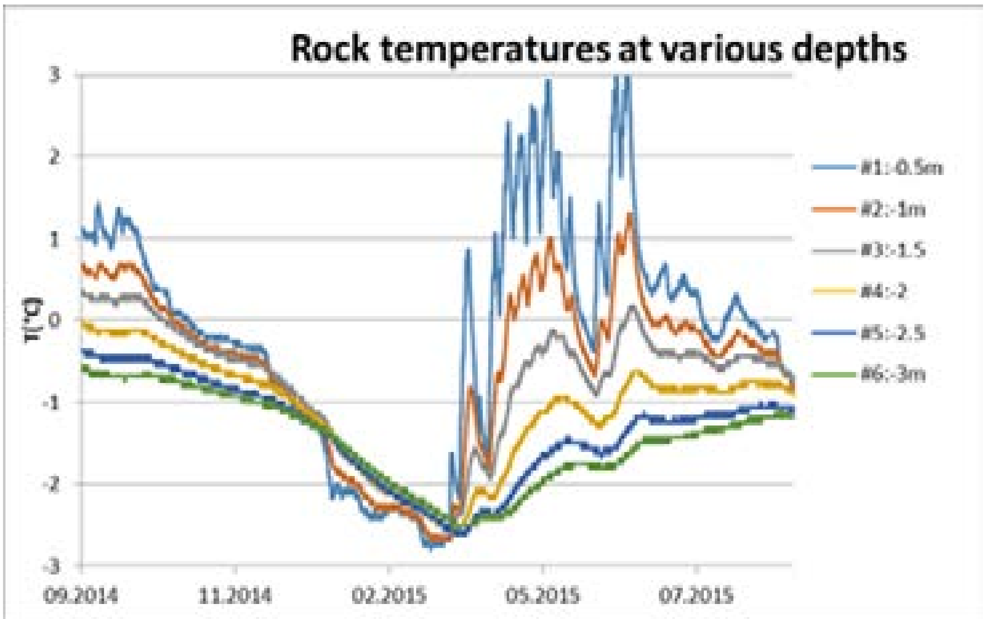
h) Force measurement at anchor load cells Accessibility Monthly to 1 time/year during critical construction phases automatic measurement
- Soil pressure under foundations
- Anchor forces of rock anchors
- Anchor tension test - when installing the anchors

4. Monitoring to assess and monitor the stability of cable car mountain stations on the Kleinmatterhorn and mountain peaks in eastern Switzerland

The Alpin X project, which is being realized by Zermatt Bergbahnen, aims to create a tourist link between Zermatt (Switzerland) and Cervinia (Italy) via the summit of the Kleinmatterhorn. To this end, two new cable car mountain stations are being built at the summit at an altitude of 3820 meters, on the 50° to 70° inclined rock faces. In these serpentinite rock faces, extensive rock excavation work of approx. 10,000m3 and rock stabilization had to be carried out over a length of 60m and a height of approx. 50m. Special challenges were posed by unstable rock sections close to the surface and the prevailing permafrost conditions. Rock mechanical monitoring, which records rock displacements, rock temperatures and the loads on the rock anchors, is an important part of ensuring safety during the construction work and in the following years of operation.

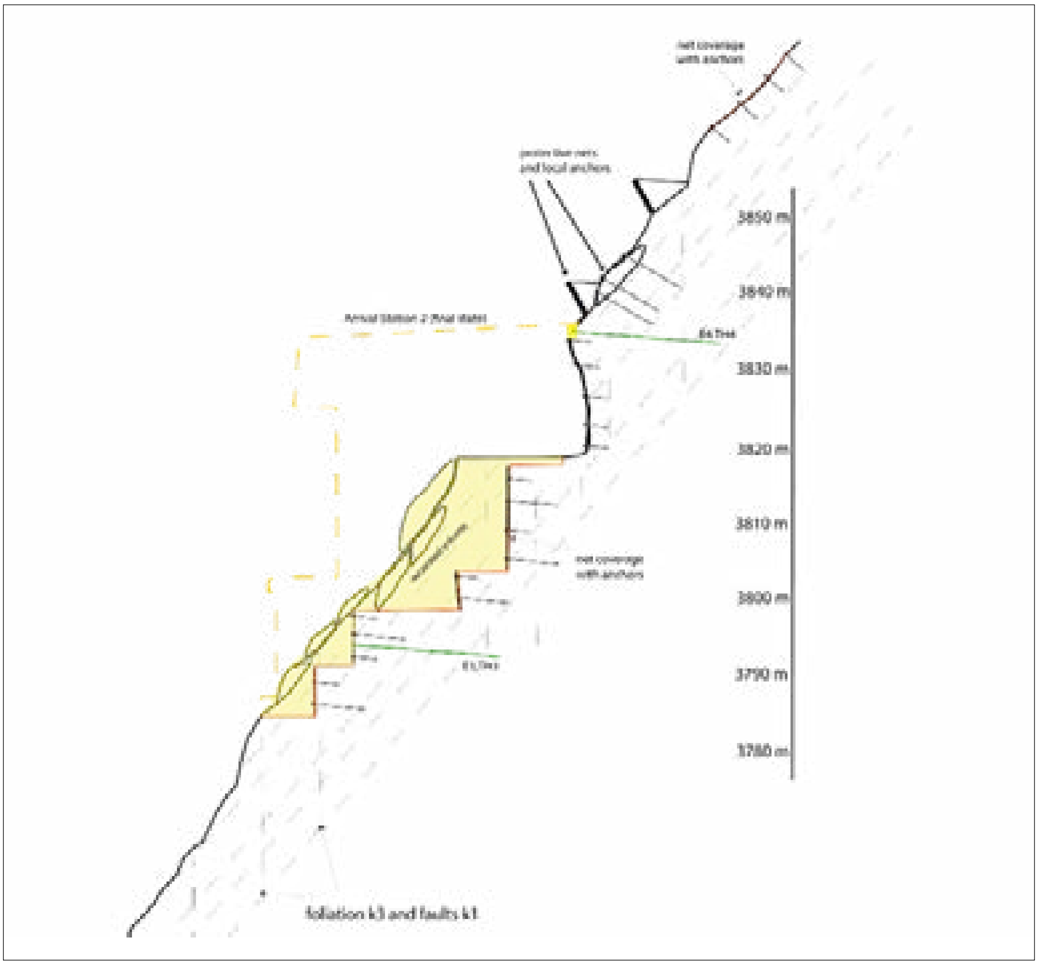
Strongly foliated serpentinite at the excavation front. (b) Typical superficial undulated rock flakes

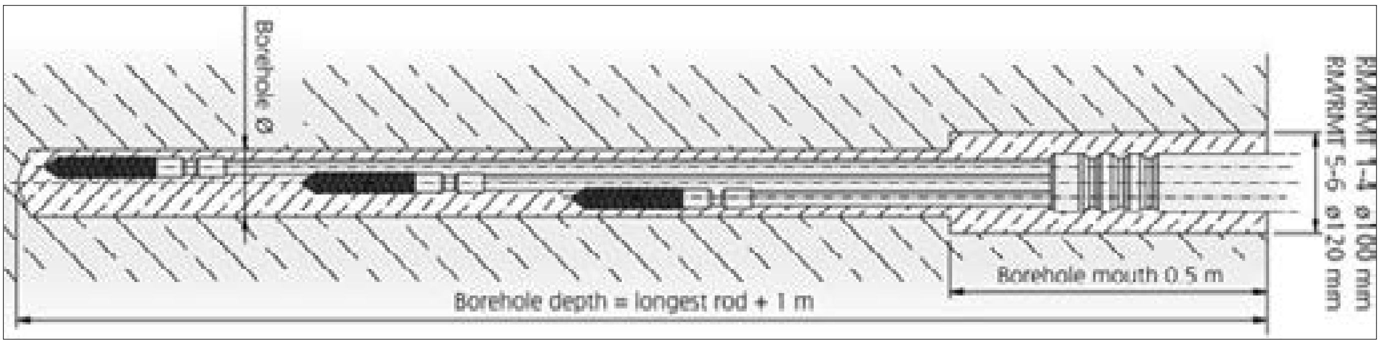
Due to the high altitude of the construction site, the prevailing permafrost conditions within the rock massif must be taken into account. This leads to a consistently negative rock temperature from a depth of around 2 meters, while the rock temperatures in the layers near the surface are subject to strong seasonal fluctuations and become positive in summer, forming the so-called active zone. This rock temperature configuration leads to the existence of ice fillings of small extent within the stratification or cracks of the shallow and near-surface layers, some of which thaw and drain around mid-June. The extent of the permafrost body within the Klein Matterhorn tends to decrease due to global warming and local activities related to existing facilities and structures. This leads to a progressive increase in the thaw layer combined with an increase in rock instability in the near-surface layers.



In order to detect possible rock instabilities in the deep rock layers below and behind the station, displacements on both sides of existing intersecting discontinuities and a possible warming of the rock temperatures are monitored with the aid of 4 triple borehole extensometers with steel rods (E1-E4) and 4 triple borehole thermistors (TH1-TH4). These instruments were installed in boreholes inclined 10° downwards, drilled at the lowest levels of the excavation platform and directly below the roof support areas. They provide measurements at 3 different depths between 5 and 30 meters. So far, no significant shifts have been detected, while the temperatures in the rock are still below 0°C, but show a slight warming.

Green line: Borehole extensometers and temperature string installed in boreholes





Borehole extensometer head (type Huggenberger) with cables of temperature string

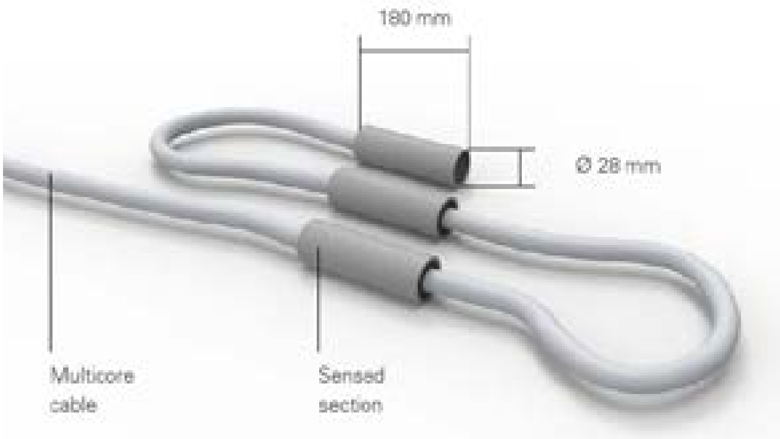
View from the Klein-Matterhorn towards the famous Matterhorn mountain

5. Cableway summit station in eastern Switzerland

Another project demonstrates rock mechanics monitoring on a mountain peak in eastern Switzerland. The mountain station, located at an altitude of around 3100 meters, is anchored on rock (serpentinite) in the permafrost. Changing climatic conditions can cause the frost zone to change and thus affect the stability of the abutment. Systems installed in boreholes for 3D displacement measurement and temperature measurement will provide important indications and information in the coming years with regard to any necessary stabilization measures. There the serpentinite is heavily eroded. This eroded zone extends to greater depths of approx. 5-8 meters. As the permafrost degrades, the shear strength and compressive strength decrease massively and settlements and horizontal displacements occur.

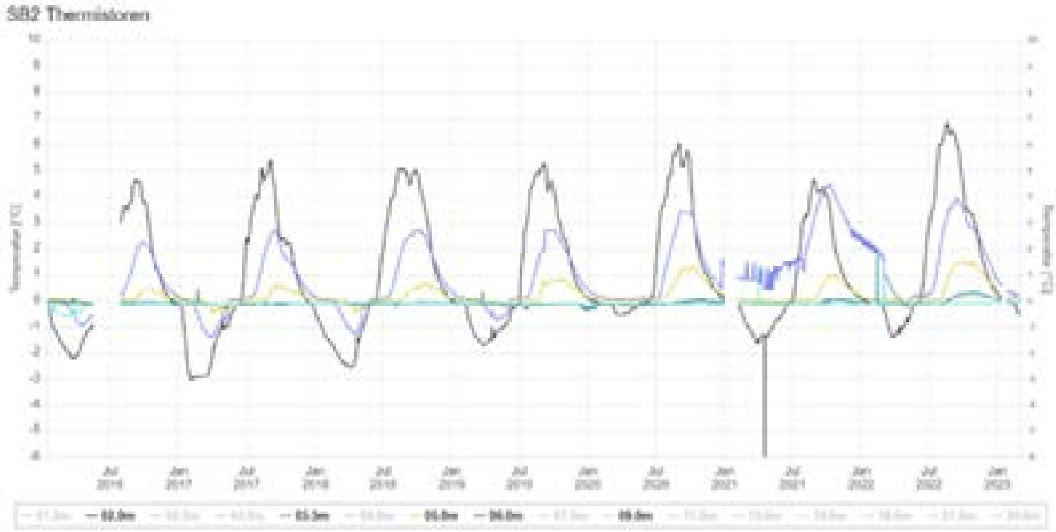
Rear area of the summit station

Inclinometer -Magnet-Extensometer borehole casing prepared to have the temperature strings attached: ready to install

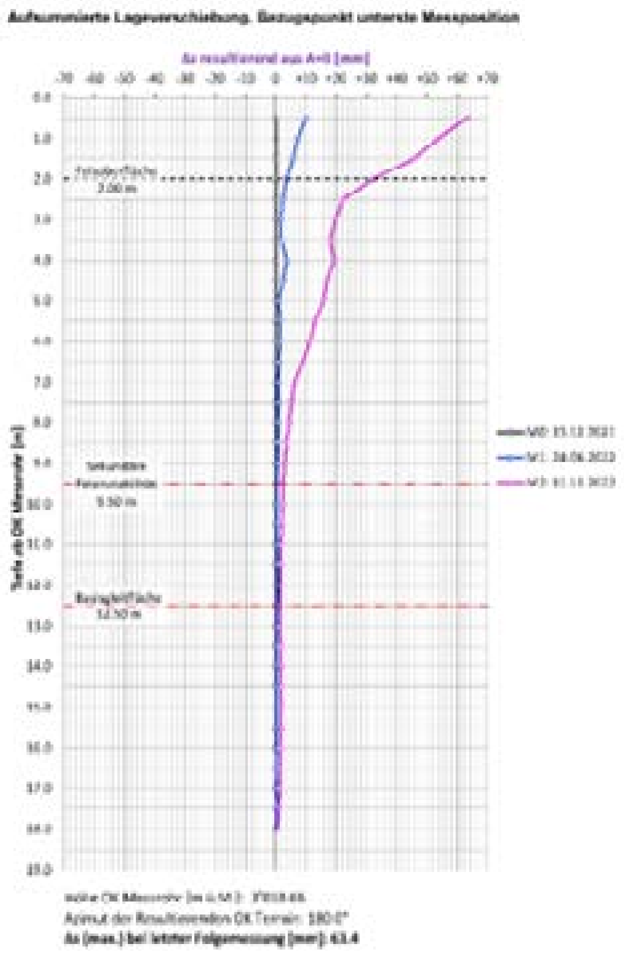


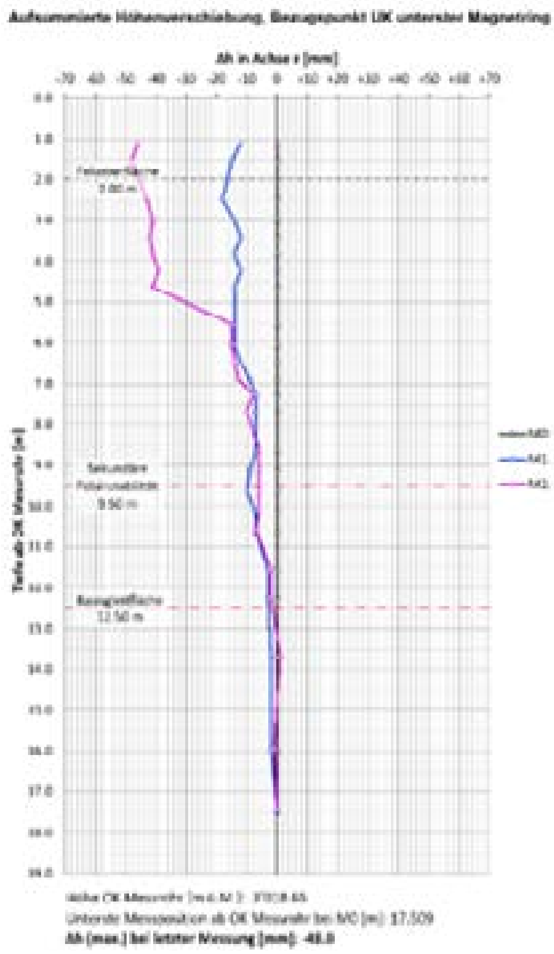
Thermstor String

Rock temperatures over past 8 years and at various depths



Horizontal and vertical deformation in deformation profiles





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