A new permafrost and mass movement monitoring test site in the Eastern Alps – concept and first results of the MOREXPERT project

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Abstract

The project MOREXPERT (Monitoring expert system for hazardous rock walls) initiates a new long-term monitoring site with the focus on permafrost and mass movement interaction at the Kitzsteinhorn (3,203 m), Hohe Tauern, Austria. Based on a combination of geotechnical, thermal, geophysical and laboratory measurements, surface and subsurface conditions are monitored at the Kitzsteinhorn. Short and medium term responses of ground thermal regime and their influence on slope stability will be investigated with respect to climate change. The project started in 2010 and this paper should therefore be read as a progress-report, initial results clearly demonstrate the need for long-term monitoring.

Keywords: slope stability, rockfall, permafrost, monitoring, climate change adaptation, natural hazards

1 Introduction

Instability of rock faces in high mountain areas is an important risk factor for man and infrastructure, particularly within the context of climate change and recent warming (Gruber et al. 2004). Numerous rockfall events in the European Alps suggest an increasing occurrence of mass movements due to rising temperatures in recent years. During the hot summers of 2003 and 2005 a large number of rockfall events were triggered from steep bedrock areas affected by permafrost without preceding precipitation or earthquake (Gruber & Haeberli 2007). In several cases massive ice was visible in the exposed detachment zones (Bommer et al. 2009). Permafrost warming and thaw are considered to be decisive mechanisms through which climate influences ground thermal regime, slope stability and therefore the occurrence of natural hazards.

In general permafrost is defined as lithosphere material that remains at or below 0 °C for more than two years. However, permafrost is a thermal regime, defined by temperature and time. Permafrost is not visible, changes in distribution and dynamics are not easily to detect. Mountain permafrost research is a young scientific discipline that systematically started in the early seventies (Haeberli et al. 2010). Long-term data series on permafrost conditions, comparable to meteorological data, are limited, but essential for understanding of permafrost dynamics and related processes.

Unfortunately, most geomorphic studies or processes are carried out fewer than three years (Selby 1993), hence the validity of short-term process measurements is at best uncertain, at worst they are irrelevant (Conacher 1988). For this reason the projects Permafrost and Climate in Europe (PACE, Harris et al. 2001), the Swiss Permafrost Network (PERMOS 2010) and the Permafrost Long-term Monitoring Network (PERMANET 2011) initiated permafrost monitoring (temperature and kinematics) in the European Alps with more than 40 sites. Especially high mountain peaks in the western European Alps like Schilthorn (CH), Matterhorn (CH), or Aiguille du Midi (F) have been instrumented for continuous monitoring of permafrost (PERMOS 2010; Ravanel et al. 2011). In Austria, extensive monitoring (e.g. with deep boreholes and geophysics) of permafrost is limited to very few sites (e.g. Hoher Sonnblick).

The project MOREXPERT initiates a new long-term monitoring site with the focus on permafrost and mass movement interaction at the Kitzsteinhorn, Austria. The project is embedded within the frame of the alpS – Centre for Climate Change Adaptation Technologies located in Innsbruck, Austria. The three main objectives in the project MOREXPERT are:

1. On a theoretical level the development of a combined methodological approach to analyse the thermal regime of the subsurface and the influences on mass movements. This includes the assessment of the influence of lithology and discontinuities on permafrost distribution and dynamics. The generated information can provide important values for permafrost distribution, and slope stability model validation. These new long-term data series will be contributed to existing national and international scientific networks, for example validation of the PERMANET map of permafrost distribution in the European Alps (PERMANET 2011).
2. On a technical level MOREXPERT will develop an easy to use and maintainable monitoring system with respect to cost and benefit. In a high-mountain environment technical challenges include, for instance, the installation of measuring instruments in steep and inaccessible terrain and the robust design of measuring instruments to resist low temperatures and natural hazards (e.g. lightning or rockfall).
3. The development of an expert system which will consist of (i) a combination of most appropriate methods and techniques; (ii) an assessment of required data resolution; (iii) an efficient data analysis and documentation.

2 Study area

The study area was selected for the following reasons:

- Glacier-permafrost interaction
- Long data series (e.g. glaciology)
- “Homogenous” lithology
- Pyramid shape of the summit
- Gallery as “natural” laboratory
- Excellent logistics

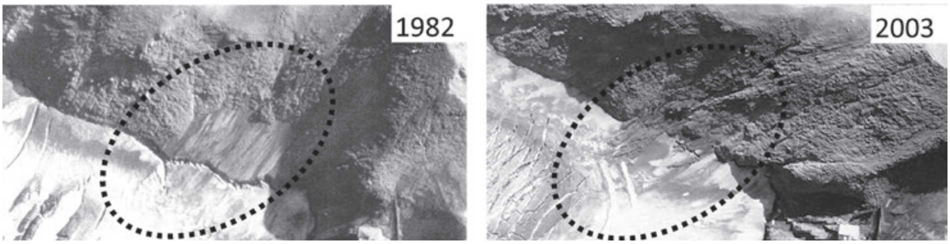

Figure 1: Rock fall and debris flow depositions underneath ice-free rockface in 2003 as opposed to 1982 (SAGIS).

The study area is located at the Kitzsteinhorn (3,203 m), situated in the Hohe Tauern, the highest mountain range in Austria. The area covers approximately 35,000 m² and extends from the top of the Schmiedingerkees glacier (2,950 m) to the summit of the Kitzsteinhorn, comprising the whole summit pyramid. The special shape of the summit also called "Karling" is perfect to analyse the influence of exposition on the subsurface thermal regime. The study area consists of rocks of the Glocknerdecke, primarily of limestone-micaschists.

Easy access of the study area is necessary for extensive monitoring, cable cars and snowcats allow quick transportation of man and heavy field equipment. The West ridge of the Kitzsteinhorn is tunnelled by a gallery 400 m in length. The gallery enables a "view inside" the mountain; discontinuities and permafrost related ice is visible in some locations. Additional the acquisition of data from greater depths (up to 50–80 m to the surface) under relative uniform conditions (no meteorological impact, low variability in air temperature) is possible.

Intense glacier retreat in recent years and decades has led to a very dynamic glacier-permafrost interaction at the Kitzsteinhorn. Due to the ongoing retreat of the Schmiedingerkees glacier some rock faces have lost their natural counter bearings creating oversteepened cirque walls. The joint set configuration in these oversteepened walls contributes to the frequent occurrence of small and medium-scale rockfall events, which are investigated within MOREXPERT. Particularly the melting of ice faces led to an increased occurrence of mass movements (Figure 1).

An abundance of historical data on glaciology and meteorology allows the compilation of long time series that help to estimate the consequences of climatic changes over the last century.

3 Conceptual approach and methods

3.1 Complementary/combined monitoring strategy

The monitoring system comprises various methods that allow complementary acquisition of climate/meteorological, surface and subsurface information relevant for permafrost and slope stability investigations. As a consequence data on changes occurring at the surface (e.g. rockfall events) can be directly related to potential meteorological and subsurface (thermal) changes (e.g. deepening of active layer). The

Table 1: Methods applied within the MOREXPERT project.

Applied methods	**Permanent monitoring**	**Periodical monitoring**
Geophysical methods		
• Electrical Resistivity Tomography (ERT)	✓	✓
• Ground Penetrating Radar (GPR)	x	✓
Geotechnical methods		
• crackmeter	✓	x
Laserscanning		
• terrestrial laserscanning	x	✓
• airborne laserscanning	x	✓
Borehole temperature data		
• deep boreholes (20–30 m)	✓	x
• shallow boreholes (80 m)	✓	x
Climate data		
• meteorological station	✓	x
Mapping techniques		
• geomorphological mapping	x	✓
• geotechnical/geological mapping	x	✓

temporal scale of investigation within our monitoring concept depends on the observed process. It ranges from permanent monitoring for very dynamic processes (e.g. frost dynamics) to time-section monitoring on a seasonal or annual basis for less dynamic processes (e.g. reaction of rock temperatures in great depths). Table 1 shows an overview of the used methods divided into permanent and periodical monitoring.

The density of monitoring instrumentation depends on the areas of interest. In areas with higher surface and subsurface dynamics and potential damage of infrastructure, the highest instrumentation density was chosen (Figure 2). The use of complementary methods, for example long-term borehole measurements with permanently installed geophysics should lead to a better understanding of the local processes. For example temperature measurements of deep boreholes deliver point information. In combination with resistivity values of the permanent installed ERT and laboratory calibration, the spatial distribution of subsurface temperature can be analysed (refer to Krautblatter et al. 2010).

3.2 Monitoring of meteorological and climate conditions

Climate influences ground surface temperature and the ground thermal regime. Hence, knowledge of meteorological variables such as air temperature, solar radia-

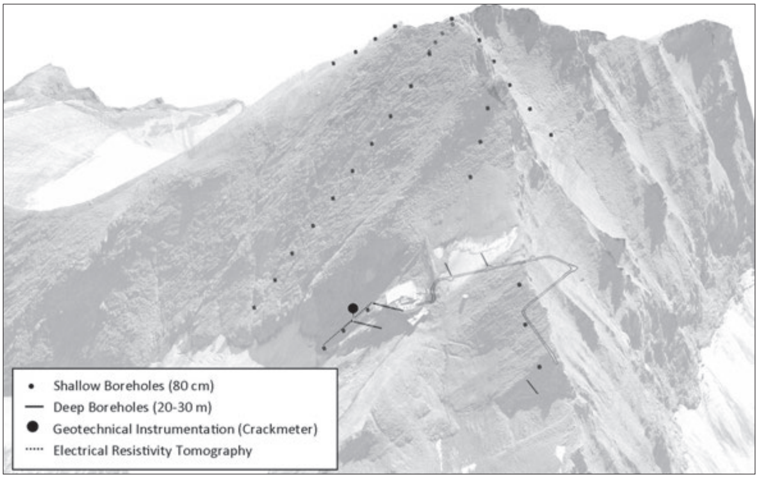

Figure 2: Overview of permanently installed monitoring instrumentation (SAGIS).

tion, precipitation or snow cover is crucial for the understanding of the thermal state of permafrost-affected bedrock and its potential future development. Within the MOREXPERT project climatic conditions will be monitored with two weather stations located on the Schmiedingerkees glacier and at the alpine center. Complementary to these stations is the use of meteorological and climate data from the Sonnblick Observatory (distance 25 km).

3.3 Monitoring of surface conditions

For spatial and temporal investigation of erosive processes occurring in the Kitzsteinhorn study area we will carry out repeated surface measurements using Terrestrial Laserscanning (TLS). TLS allows accurate quantification of changes in geometry and volume in steep terrain over distances of up to several hundreds of meters (Kenner et al. 2011). Information gained from TLS monitoring should yield "hot spots" of rockfall activity. The types of mass movements investigated range from single rock falls with volumes less than 1m^3 to medium-scale rock and block fall events with volumes of several thousand cubic meters.

In addition TLS data will yield information on rock mass properties (e. g. joint orientations). This is of particular interest since the configuration of joint sets often represents the primary disposition for the occurrence of rockfall. For that reason discontinuity extraction from TLS data is performed that is expected to offer new explanations of the spatial occurrence patterns of rockfall.

Additional to TLS monitoring a network of local observers will be organized to register the occurrence of rockfall events. This network of observers will consist of local employees working in or close to the study area (cable car attendants, mountain rescue etc.) who are asked to record observed rockfall events in a standardized questionnaire. This approach will provide a qualitative and semi-quantitative assessment of rockfall events.

3.4 Monitoring of subsurface conditions

3.4.1 Thermal conditions

The occurrence of permafrost and thickening of the permafrost active layer in steep bedrock potentially causes large and therefore extremely hazardous rockfall events with deep-seated detachment surfaces. There are two strategies for investigating thermal conditions. To assess permafrost distribution, up to 60 temperature loggers are installed in depths of 10 to 80 cm to measure near-surface rock temperatures and thermal offsets (Hasler et al. 2011). The temperature loggers are spatially distributed over the summit pyramid.

To investigate permafrost and active layer dynamics five boreholes with depths between 20 and 30 m were drilled. Each borehole will be equipped with 12 temperature loggers (thermistors) allowing precise measurement of ground temperatures.

3.4.2 Geophysical investigations

Two permanently installed 2-dimensional ERT-arrays (Electrical Resistivity Tomography) are used for monitoring subsurface resistivity conditions. The measurements are taken at two different scales. A very high resolution array with a penetration depth of 2 m is used for monitoring near surface dynamics (e. g. frost dynamics). For deeper process changes (e. g. active layer dynamic) a second array with a depth up to 20 m will be installed. Additional ERT measurements will be conducted at several sites including the gallery with a lower frequency.

Knowledge of the subglacial terrain of the currently glacier-covered area is necessary for future projections. To record the decreasing ice thickness of the Schmiedingerkees glacier and to estimate the characteristics of the subglacial terrain we will conduct repeated GPR (Ground-Penetrating Radar) measurements. Newly exposed rock surfaces become subject to freeze-thaw cycles and greater temperature amplitudes. As a result they usually represent (oversteepened) zones that are particularly susceptible to rockfall. Knowledge of these zones is important for the designation of areas that are potentially affected by future rockfall events in a warming climate.

3.4.3 Joint dynamics

Within the MOREXPERT project the joint aperture will be continuously monitored at two locations using wire-extensometers that are connected to data loggers. Changes of the joint aperture combined with geophysical and thermal monitoring can give valuable information on freezing dynamics.

4 First results

4.1 Geotechnical survey and slope stability analysis

For the ground thermal regime and slope stability analysis detailed information about the rock mass is essential. Tectonic, stress release and intense physical weathering processes, typical for periglacial environments, developed joint sets with large apertures in the study area. First geotechnical surveys were conducted which delivered valuable data on joint orientations and descriptive characteristics as well as on block size and shape. Major joint sets K1 and K2 are dipping steep to W and SW, respectively, whereas schistosity is dipping moderately to NE. Subordinate to the major joint sets are K3, dipping medium to flat to S-SSE and K4, dipping steep to NW. An intersection of these three major joint sets yields cubic, joint-bordered rock bodies, frequently of considerable size (Figure 3).

The joint sets can be divided into two generations. On the one hand, an older generation which is filled with either quartz or calcite, and is usually based on the major joint set K2 and on the other hand a recent generation with joint aperture ranges from a few millimetres up to 20 cm in all joint sets. Four rock probes were taken and analysed in the cold laboratory at the University of Bonn. Shear tests (Figure 4) have been applied under frozen and unfrozen conditions; in combination with the captured parameters from the first geotechnical surveys and literature values an initial UDEC slope stability model will be developed.

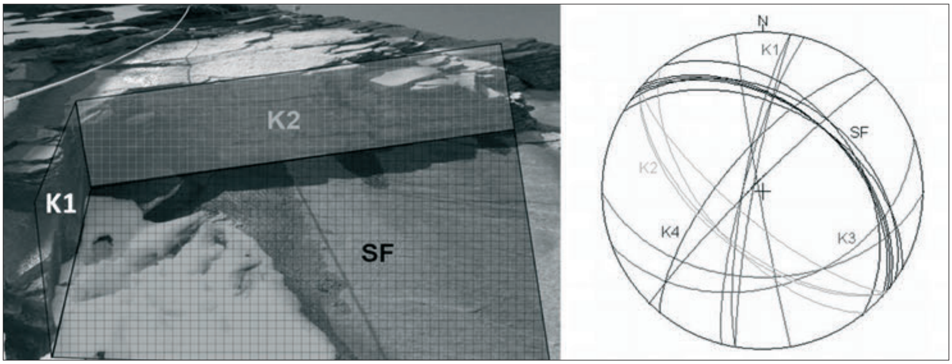

Figure 3: Major joint sets (K1, K2) and schistosity (SF) and their orientation in space.

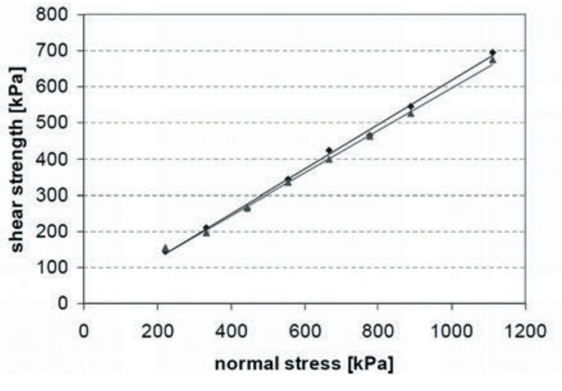

Figure 4: Shear-normal stress curves for the series of experiments with normal stresses between 222 kPa and 1.1 MPa. Internal friction angles of 31.6 and 30.5 degrees have been measured for the frozen (steep curve) and unfrozen test runs, respectively. The curves of frozen and unfrozen passages are very close together. Maximum differences of the peak shear strength amount to 30–50 kPa.

4.2 Permafrost modelling

Rock faces affected by permafrost are expected to react particularly sensitive to future climatic changes. Knowledge of permafrost distribution is therefore critical for slope stability assessment. A permafrost distribution model using an advanced version of the PERMAKART model (Ebohon & Schrott 2008; Keller 1992) was applied. This model is an empirical-statistical model based on a topo-climatic key which analyses the relation between altitude, slope, and aspect (with foot-slope positions being taken into account as well). First model results reveal that large areas of the Kitzsteinhorn study area are underlain by permafrost. Especially the northwest and, to a lesser degree, the northeast face of the Kitzsteinhorn displays a very high probability (>75%) of permafrost occurrence (Figure 5).

4.3 Electrical Resistivity Tomography (ERT)

Due to a significant increase of electrical resistivity at the freezing point ERT is very well suited to distinguish frozen and unfrozen subsurface regions. The strong correlation between electrical resistivity and temperature makes repeated ERT measurements a proficient tool to monitor subsurface thermal changes (Krautblatter et al. 2010).

A high-resolution ERT was applied inside the subterranean gallery (tunnel) crossing the Kitzsteinhorn west ridge. The ERT-array was installed in the eastern side wall of the gallery yielding a horizontal (eastbound) direction of investigation. The vertical bedrock overburden of the gallery ranges from approximately 15 to 70 m. The maximum depth of investigation was 21 m (Figure 6).

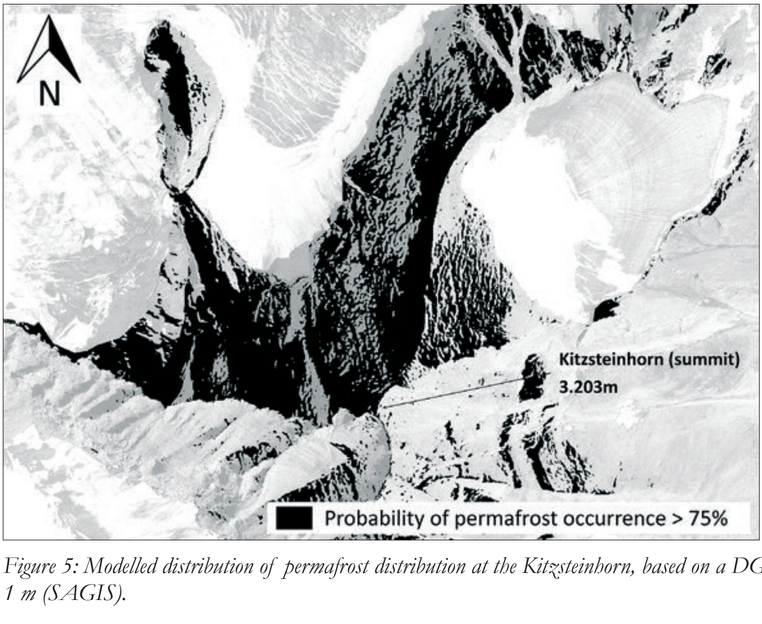

Figure 5: Modelled distribution of permafrost distribution at the Kitzsteinhorn, based on a DGM with a resolution of 1 m (SAGIS).

Preliminary interpretation of ERT data proposes the existence of permafrost-affected rock in the northern part of the tomography as resistivity values measured in this area correlate with temperatures well below the freezing point. The central part of the tomography represents unfrozen rock. Resistivity values in this area clearly correlate with temperatures above the freezing point. The south (right) section of the tomography is influenced by its vicinity to the Kitzsteinhorn south wall (vertical overburden approx. 15 m). In a comparatively short period of time seasonal frost (from a cold spell during June 2010) presumably penetrated through open joints yielding subzero temperatures (high resistivities) in this area. This observation is highly notable but still has to be confirmed by further ERT measurements and direct temperature monitoring. Despite the uncertainty these observations seem to emphasize, once again, the importance of joint systems as zones of enhanced heat propagation that react sensitively to thermal changes.

To gain thermal information from the data acquired in the gallery we conducted a laboratory calibration (Figure 7) to establish a relationship between electrical resistivity and temperature. Using four 40 × 20 × 20 cm limestone-micaschist samples taken from the study site, electrical resistivity as a function of temperature was measured.

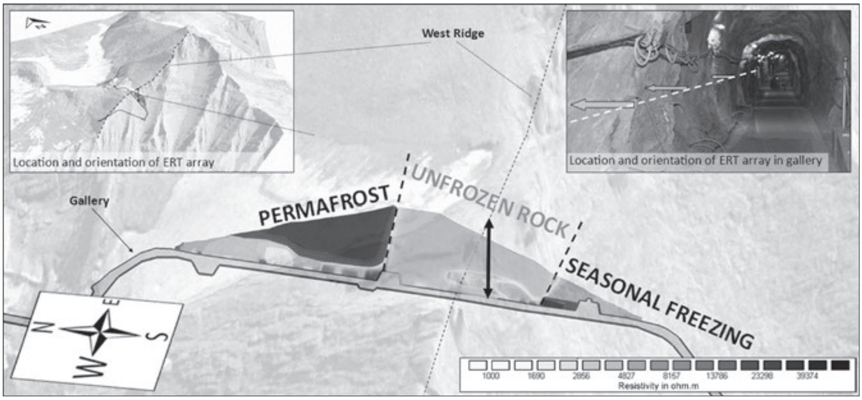

Figure 6: Location, orientation and tomography of ERT conducted inside the Kitzsteinhorn gallery (25.06.2010, SAGIS).

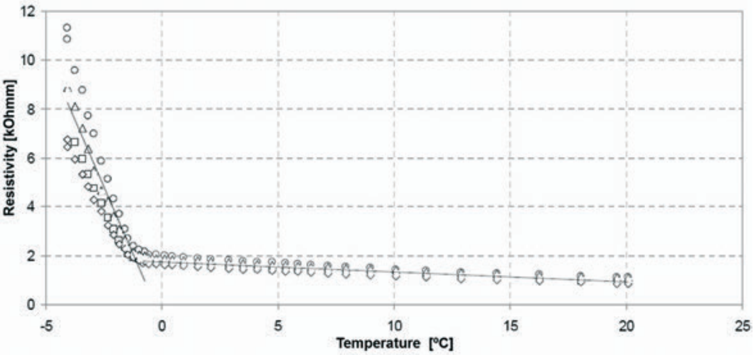

Figure 7: Resistivity-temperature plot of the four-point-Wenner array.

The water-saturated rock sample was frozen and thawed numerous times in a freezing chamber. During the freeze-thaw-cycles a four-point-Wenner-array configuration was conducted which eventually confirmed the bilinear temperature-resistivity relationship established by Krautblatter et al. (2010).

Final interpretation of the acquired ERT data will be done when petrophysical data is available.

5 Conclusion and outlook

The Kitzsteinhorn monitoring site is one of Austria's most important reference test sites for permafrost and mass movement research in a high mountain environment. Geotechnical investigations seem to be the most important step in this early stage of the project. Especially quantitative analysis of the rock mass, for example with TLS data, or from laboratory tests, are necessary and will be intensified to improve slope stability analysis and rockfall modelling.

Permafrost has been modelled and detected within the north face of the Kitzsteinhorn peak. First laboratory analysis delivered a calibration of ERT values and rock temperature. Until spring summer 2012 five boreholes (20 to 30 m) and 60 near surface boreholes will be instrumented with thermistors. In addition, we will install two permanent ERT arrays below the summit station. The gathered information should provide a solid basis to establish a monitoring expert system.

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