

Short Communication

Practical Recommendations for Planning, Constructing and Maintaining Infrastructure in Mountain Permafrost

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ABSTRACT

Mountain infrastructure can be negatively affected by ground-ice degradation induced by the combined effects of construction activity, the structure itself and climate change. Modification of subsurface conditions may cause differential settlement, creep and deformation of structures, substantially shortening their service life. Permafrost detection techniques and adaptive design methods taking into account changes in the geotechnical properties of the ground are rarely applied on construction sites in the Alps. The analysis of potential structural sensitivities to changes in the substrate and the determination of failure consequences are necessary for the successful design of durable infrastructure. Appropriate monitoring systems allow timely diagnoses and the application of suitable remedial measures. The use of specially conceived technical solutions in mountain permafrost is becoming widespread, yet there is not a commonly accepted state-of-the-art. New recommendations provide an overview of practical solutions for the construction and maintenance of durable infrastructure in mountain permafrost. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: mountain permafrost engineering; site investigation; consequences/sensitivity analysis; monitoring; technical solutions

INTRODUCTION

Engineering structures located in mountain permafrost in the Alps are currently being affected by the consequences of permafrost degradation (Arenson *et al.*, 2009; Harris *et al.*, 2009). Changing subsurface conditions are potentially problematic as they can induce differential settlement by soil creep and deformation, shortening the design life of an engineering structure and causing safety concerns as current factors of safety may be lower than design values. In some cases, inappropriate technical solutions have been applied due to a lack of awareness of permafrost phenomena and their potential impacts. In addition, the combined effects of construction, use and climate change on the geotechnical properties of ice-bearing frozen ground during the service life

of a structure are not always adequately accounted for during the design process. There are several examples of existing infrastructure in mountain permafrost that have required adaptation or even reconstruction after a much shorter than anticipated service life (Arenson *et al.*, 2009; Haeberli, 1992; Phillips *et al.*, 2007; Phillips and Margreth, 2008). The success of a construction project in mountain permafrost requires an interdisciplinary approach and relies on efficient communication between the fields of science and engineering (Haeberli, 1992) during all stages of design, construction and use.

Developments in permafrost engineering have mainly taken place at high latitudes (e.g. Andersland and Ladanyi, 2004; Instanes *et al.*, 2005; Tsyrovich, 1975). In high mountains, bedrock and coarse sediments dominate and the topography represents an additional engineering challenge. With the exception of the Swiss guidelines for the construction of avalanche defence structures (Margreth, 2007), there have been no design aids or recommendations available for Alpine infrastructure. Given their high socio-economic relevance, new recommendations have been developed to limit both cost and uncertainties in the future

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by focusing particularly on site investigation and the choice of appropriate foundation designs (Bommer *et al.*, 2009).

This short communication presents the engineering challenges and practical solutions of special interest with regard to the design, construction and maintenance of infrastructure in mountain permafrost.

HIGH-ALTITUDE CONSTRAINTS

The expected effects of climate change include the observed warming of air temperature in the Alps and in addition a decrease in precipitation during summer, increased precipitation during winter and more intense precipitation events and heat waves (IPCC, 2007). Changes in the atmosphere will also affect solar radiation intensity. The direct consequences for mountain permafrost regions include rockwall instability (Davies *et al.*, 2001; Gruber *et al.*, 2004), an increase in the occurrence of slow and rapid mass movements (Haeberli and Gruber, 2008; Harris *et al.*, 2001), a deepening of the active layer, thermokarst development and decreased shear strengths (Arenson *et al.*, 2007), which can ultimately affect structural stability (Phillips and Margreth, 2008). Indirect consequences on ground temperature are also expected as a result of the changing snow cover timing and duration (Luetschg *et al.*, 2008). All of these factors, in combination with the influence of construction activity and the thermal disturbance effect of the structure itself, can modify the substrate conditions in mountain permafrost during a structure's service life and must therefore be considered in the design process.

The time frame available for construction in high mountain regions may be shorter than in surrounding valleys and special measures may be required. Harsh weather conditions, including rapid changes in conditions, and high altitudes, result in a decreased performance of both humans and machines. Site access is often difficult, complicating transport and significantly raising overall costs. At exposed locations there is an increased potential for geohazards, implying that adequate protection measures must be installed or a change of location considered.

PRELIMINARY STUDY

An important prerequisite for guaranteeing the longevity of infrastructure in mountain permafrost is a sufficiently detailed preliminary study. This may result in higher initial costs but the service life will be longer and construction and maintenance expenses lower. The first and most essential step is to determine whether permafrost with ground ice is present, as this will influence the entire subsequent design procedure.

Permafrost Detection

Failure to recognise the presence of ice-bearing permafrost has in the past induced a significant reduction in the service

life of some structures in mountain permafrost, whereas infrastructure at sites where permafrost detection methods were carried out and the project design adapted accordingly have long service lives (Haeberli *et al.*, 1979; Keusen and Haeberli, 1983; Steiner *et al.*, 1996).

The distribution of permafrost in mountainous environments is affected by a number of factors and perennially frozen ground can be found at a wide range of altitudes, aspects and in various terrain types. The systematic application of certain tools and methods is therefore necessary for the investigation of the potential distribution of permafrost (Harris *et al.*, 2001), a practice that has been prescribed for decades in permafrost regions at high latitudes (Johnston, 1963; Tsytoich, 1975).

A stepwise screening procedure is required to verify whether permafrost is present and above all, it is essential to determine whether the ground contains ice or not. In a series of increasingly detailed, time-consuming and costly analyses, consisting of preliminary investigations, *in-situ* observations and field measurements, the likelihood of encountering permafrost and ground ice at a given site can be determined. In a final stage, the presence of permafrost is definitively confirmed or rejected using trenches and/or boreholes. Only then can appropriate structure designs and specially adapted technical measures be applied.

Geotechnical Investigations

Various field and laboratory tests should be carried out to determine the geotechnical characteristics of frozen ground, in particular temperature distribution, and mineral, ice and unfrozen water contents (Arenson *et al.*, 2009; Bommer *et al.* 2009). The bearing capacity and strength of the ground and its changes with time and temperature strongly depend on these.

In-situ tests such as flat dilatometer or cone penetration tests, commonly used to characterise geotechnical parameters in non-permafrost terrain, are practically impossible to carry out in the coarse-grained materials typically found in mountain permafrost. Borehole pressure-meter tests can only be performed in relatively stable boreholes (Arenson, 2002). The extraction of undisturbed samples for laboratory testing requires special drilling techniques, experienced personnel, and special transportation and storage methods entailing particular logistics. Laboratory tests include uniaxial and triaxial compression tests and direct shear tests (Arenson *et al.*, 2009).

CONSEQUENCES AND SENSITIVITY ANALYSIS

Until now, the combined impacts of construction, infrastructure and climate change on both the substrate and on the structure itself were rarely taken into account in the planning and construction of mountain infrastructure. Adaptation techniques (Hayley and Horne, 2008; PERD, 1998) provide an excellent basis for the design of safe, durable infrastructure. The consequences and sensitivity

analysis presented in the PERD (1998) report for northern infrastructure can readily be adapted to mountain permafrost.

The analysis determines the sensitivity of the substrate in permafrost to different effects, such as changing ground temperature and ice content. Based on the project description, an initial substrate characterisation and an assessment of possible effects, the sensitivity to different effects can be determined (Figure 1).

Various failure consequences can occur, depending on the type of infrastructure and its location. The relevance of an effect can be determined qualitatively. Differential settlement of the foundation of a mountain hut or restaurant would, for example, lead to discomfort and maintenance costs, whereas the settlement of a cableway station or pylon would result in high risks and reconstruction costs. In the latter case, the sensitivity limit for serviceability (serviceability limit state) is the limiting factor, whereas for less sensitive mountain huts or restaurants the bearing capacity (ultimate limit state, ULS) is the decisive factor (Bommer *et al.*, 2008). Depending on the building category, the project description specifies the relevant effects and their impacts on a structure. The consequences are subsequently determined (Figure 1).

Various examples of mountain infrastructure are shown in Figure 2 and the consequences of structural failure (x-axis) and the sensitivity of the structure (y-axis) depicted. This allows a qualitative classification of structures into four

categories (quadrants I–IV), allowing the required level of analysis ('Z') to be determined with regard to possible effects (e.g. of climate change) on a structure during its service life in a mountain permafrost environment.

For a temporary structure located in quadrant I (Figure 2), a detailed risk analysis and site investigation are unnecessary. However, for a cableway station or pylon in quadrant IV (Figure 2), a detailed quantitative analysis is highly recommended, including numerical modelling of the changeable effects/impacts, extensive site investigations, field and laboratory tests, engineering inspections and the use of a monitoring system during all project phases.

MONITORING

Structures in Alpine permafrost should be equipped with an appropriate integral monitoring system allowing simultaneous observation of the evolution and interaction of the permafrost substrate and infrastructure (Keusen and Haeberli, 1983; Phillips, 2006; Phillips and Margreth, 2008; Steiner *et al.*, 1996). The causes and rates of damage to structures are difficult to determine in the absence of detailed monitoring systems. This can lead to errors of diagnosis and delays in the adoption of appropriate remedial measures.

Monitoring systems should be designed and installed before construction starts and, if necessary, adapted during

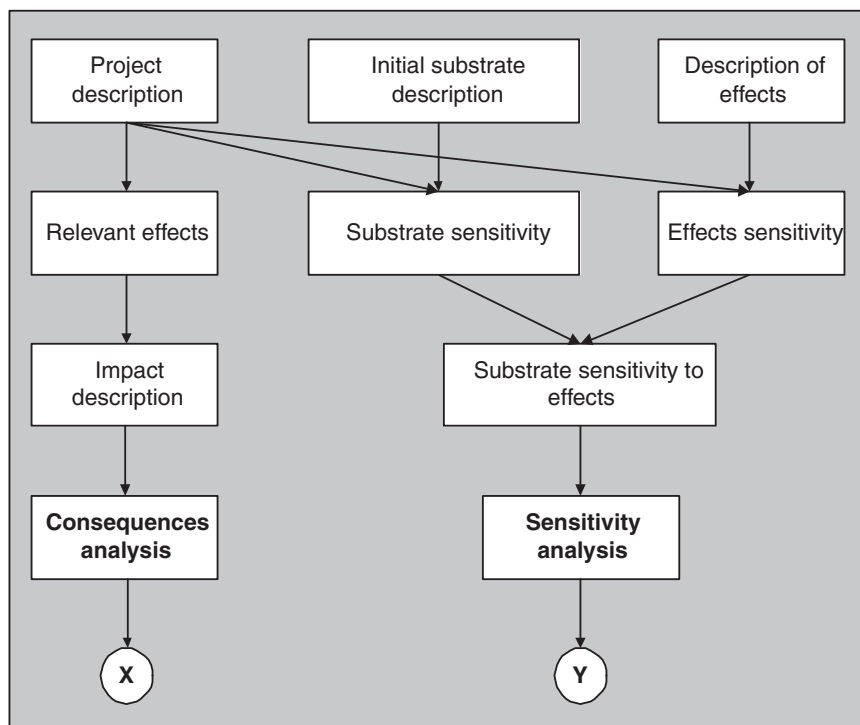


Figure 1 Flowchart of a consequences and sensitivity-screening process for infrastructure in mountain permafrost (adapted from PERD, 1998; Arenson *et al.*, 2009).

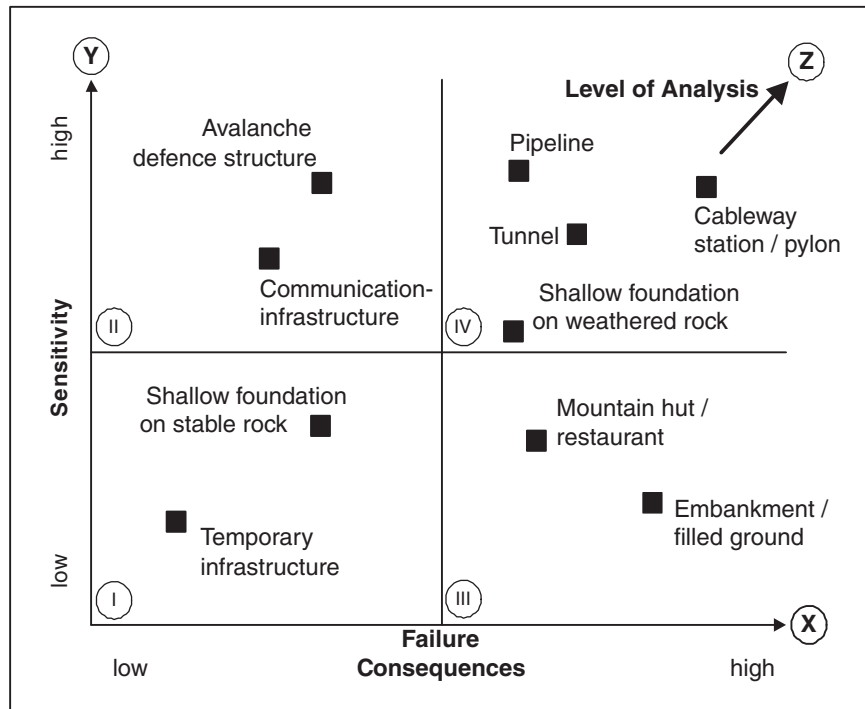


Figure 2 Categories of mountain infrastructure according to their sensitivity and the consequences of failure, allowing the required level of analysis prior to construction to be determined (adapted from PERD, 1998; Arenson *et al.*, 2009). Note: The points shown are only examples. Failure consequence and sensitivity have to be determined individually for each construction project.

and after project realisation. The installation and maintenance of a specially tailored, precise monitoring system during all project phases allows the timely identification of potential problems. Measurements can also be used as an early warning system if threshold alarm values have been predefined. Measurement frequency and responsibilities must be defined in advance, as should the safety and remedial measures to be taken in case of an emergency.

As some monitoring devices cannot be accessed after being installed or may be subject to long-term drift, redundancies should be planned. Instruments must be screened for robustness in their particular measurement environment (e.g. those embedded in concrete or in creeping substrates) and properly calibrated in the laboratory.

Numerical models often depend on high-quality *in-situ* measurements for their calibration. It is therefore essential to have a good series of field data to enable numerical modelling for design to be carried out with sufficient confidence.

ENGINEERING PROBLEMS AND SOLUTIONS IN MOUNTAIN PERMAFROST

The main challenge regarding the foundations of infrastructure and anchors in mountain permafrost is the

evaluation of their location and depth, depending on the load type and direction. If the ground is ice-rich, ideally a different site should be chosen, or the sustainability of the structural concept will be impaired. If this is not possible, specially adapted construction techniques must be applied or the project abandoned.

Flexible Foundation Systems

Adjustable flexible foundation systems are an ideal solution in ice-rich, creeping terrain. Laterally adjustable cableway pylons are now built by default in some Alpine ski resorts. Creep can, for example, be countered by the use of moveable pylons on steel rails (Figure 3).

For snow nets (avalanche defence structures) located in strongly creeping permafrost, floating foundations consisting of a steel plate on a concrete-levelling course together with swivel supports are recommended rather than fixed anchored foundations (Margreth, 2007) (Figure 4).

Three-point foundations are a suitable solution for structures such as cableway stations (Phillips *et al.*, 2007) or mountain restaurants (Bommer *et al.*, 2008). This type of foundation system is statically determined and deformations cannot create internal constraints. Differential settlements can be adjusted by uplifting the structure with hydraulic presses and inserting steel plates or by using grout.



Figure 3 A laterally adjustable cableway pylon foundation for creeping permafrost terrain. This figure is available in colour online at www.interscience.wiley.com/journal/ppp.

Anchor Systems

To reach the specified pull-out resistance (ULS), anchors must be installed with certain precautions. Boreholes ought to be flushed with cold air rather than with fluids to avoid thermal disturbances and permafrost degradation around the borehole during drilling. The anchors should be placed and the grout injected immediately in order to avoid refreezing, and to ensure a good bond with the ground.

Anchor grout injection can be problematic from several points of view. The grout can freeze before attaining the appropriate load-bearing strength, requiring preheating of the water and aggregates (Margreth, 2007). Poor grout pumpability and blockages in the injection pipe are common. Solutions to this include the use of an additive in the anchor grout (e.g. a plasticiser), or increasing the injection pipe diameter to minimise clogging. Ground water in taliks can flush out the fines from a freshly injected anchor grout, leading to a reduction of the load-bearing strength of the anchor. The use of an impervious anchor grout is a possible remedy here. Anchor performance testing is further required for each anchor to test system quality.

Excavation and Tunnelling

Excavations in frozen granular soils require the use of a backhoe or mechanical pick, whereas in bedrock or soils with high ice contents blasting is inevitable. More explosives and a denser blasting grid are required than

in ice-free terrain due to the monolithic character of ice-rich soils (Bertsov *et al.*, 1980). Excavation embankments should be covered with an insulating geomembrane in summer, to attenuate permafrost degradation and reduce the risk of slumping.

Berms are necessary for excavation pits in granular soils, with the slope angle depending on the subsoil composition and the ice content. In rock, the slope angle and the temporary excavation pit supporting systems are dictated by the pattern and orientation of the joints. A minimal protection against rockwall instability can be provided with a shotcrete lining and with a grid of rock nails. Thermal surface protection is recommended if the test pit is to be left exposed to the atmosphere, in particular to intense solar radiation, for a longer period and failure due to ice melt is expected.

Tunnelling is a widespread activity in mountains for transport purposes, mining activities or in the context of hydroelectric projects. Of ice-rich, fractured bedrock at temperatures close to 0°C, the excavation, supporting and lining techniques can be compared to those used in unfrozen granular material. Under these conditions, a shield-driving method, or traditional drill and blast technique is often used.

Substrate Removal and Improvement

Improvement of shallow foundation conditions in soils consisting of poorly graded material or heavily fractured



Figure 4 Floating foundation of a flexible snow net under a swivel support in strongly creeping permafrost (Photo: B. Dräyer). This figure is available in colour online at www.interscience.wiley.com/journal/ppp.

rock can be achieved by replacing the substrate with a well-graded, non-frost-susceptible material. Compacted gravel pads improve the bearing capacity and simultaneously distribute the load uniformly. A geomembrane, steel net or cement powder interspersed with the substrate can additionally be used for reinforcement.

In jointed rocks, improvement of the bearing capacity can be achieved with grout injections and rock nailing (Figure 5). Rock nails or micropiles are inserted in vertical or inclined boreholes and grout is injected, filling the rock fissures. The flow characteristics of the grout mixture determine its propagation. The use of fabric anchor stockings reduces grout loss. These methods result in more homogeneous foundation conditions and

increased overall stability with a certain degree of reinforcement.

Insulation and Cooling

A layer of pressure-resistant insulation (e.g. foam glass or extruded polystyrene) can be placed between the infrastructure and the ground to reduce and delay heat transfer (Phillips *et al.*, 2007). Alternatively, air spaces provide effective insulation. Heat-generating machinery should not be located in the basement of buildings. These basic permafrost-preserving methods and active cooling systems are common in the Alps, whereas the passive cooling systems that are ubiquitous at high latitudes, such as thermosyphons, are rarely seen at present.

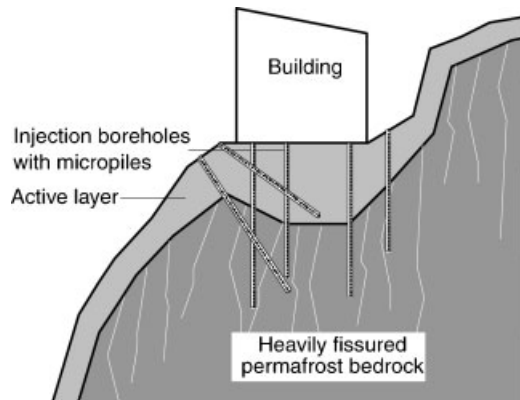


Figure 5 Schematic cross-section of a building on fissured permafrost bedrock with injection boreholes and micropiles to improve the overall stability and bearing capacity.

CONCLUSIONS

Harsh construction conditions and climate change require special attention for the design and construction of mountain infrastructure. In areas where permafrost is expected, the three most essential steps in mountain permafrost engineering projects are to initially determine:

- (1) whether permafrost conditions are present or not (permafrost likelihood),
- (2) if ground ice is present, and
- (3) the geotechnical characteristics of ice-bearing ground.

The extent of the analysis of the substrate's long-term development depends on the type of structure, its sensitivity and design life, as well as on potential failure consequences. A detailed preliminary study and the use of an appropriate integral monitoring system generate higher initial costs but result in a longer service life, lower maintenance expenses and improved numerical model confidence. The use of specially adapted technical solutions and foundation/anchoring systems further prolongs the service life of structures. New recommendations (Bommer *et al.*, 2009) present practical solutions to be applied during different phases of a high-altitude engineering project – from the preliminary study to the demolition of infrastructure at the end of its service life.

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