PERMAFROST DISTRIBUTION AND IMPLICATIONS FOR CONSTRUCTION IN THE ZERMATT AREA, SWISS ALPS

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Abstract

Zermatt is one of the prime tourist sites in Switzerland with a large number of structures built for transport and accommodation. The surrounding mountains reach altitudes of more than 4500 m a.s.l. and the areas above 3300 m are glaciated. Well developed periglacial forms and numerous rock glaciers are an expression of intense frost action. The permafrost distribution was calculated with different models and checked in the field with geophysical soundings, BTS-measurements and continuous ground temperature recordings.

The construction of larger buildings in permafrost areas has become more frequent in recent years, and these conditions demand careful considerations in environmental engineering. Whereas buildings constructed at the beginning of this century sometimes suffer from the melting of frozen ground, modern construction techniques are usually well adapted to the permafrost conditions. However, small disturbances of the permafrost environment may result in serious operation and maintenance difficulties.

Introduction

The characteristics of mountain permafrost and the basics of its distribution in the Alps have been well researched, especially since the 1970’s and 1980’s (Barsch, 1973; 1978; Haeberli, 1975; 1985; King et al., 1992). However, this information is often restricted to individual sites, e.g. rock glaciers (Fisch et al., 1977). More recently, numerical modelling of permafrost distribution has been developed to cover larger areas (Hoelzle, 1992; 1994; Keller, 1992). For verification of these models and for better modelling techniques, a wide range of information from geophysical sounding techniques is required (Barsch and King, 1989; Haeberli, 1985; Vonder Mühll, 1993). In addition, observations from construction sites (Keusen and Haeberli, 1983), tunneling and deep drilling (Funk and Hoelzle, 1992) in the mountains have become increasingly important as information sources about permafrost characteristics (e.g., temperature gradients, ice-content). This information from the deeper subsurface is also vital for questions of slope stability in the global change context (Dramis et al., 1995). The study area of Zermatt, with its long history of intense development and research (cf. King, 1996), will be one of the key areas within the European PACE project (1998-2000). This paper shows the current permafrost distribution in the Zermatt area and reviews implications for past and future construction work. Future research plans are also outlined.

Location of the area and climate

Zermatt is one of the prime tourist centres in Switzerland with about 16,000 beds and about 1 million registered overnight stays per year. Although the town itself is in permafrost-free terrain at an altitude of 1600 to 1750 m a.s.l., transportation installations for tourists reach to above 3800 m a.s.l., well into continuous permafrost. Zermatt is surrounded by mountain ranges...
that surpass 4500 m a.s.l. with a glacial equilibrium line at about 3300 m a.s.l. (Figure 1). These ranges generate large glaciers, but also vast periglacial areas due to reduced precipitation in the lee of the mountains. Here, well-developed periglacial forms (solifluction tongues, patterned ground and numerous active, inactive and relict rock glaciers) are an expression of intense frost action in a fairly continental climate.

The mean annual air temperature (1960-1990) is +3.7°C at Zermatt (1610 m), and the calculated values for Gornergrat (3135 m) and Kleinmatterhorn (3820 m) are -4.1°C and -7.6°C, respectively (Figure 2). The mean annual precipitation varies largely due to the topography and is as low as 700 mm at Zermatt. Estimates for the investigated permafrost areas between the elevations 2500 m and 3500 m range between 1500 mm and 2500 mm. Heavy snowfall is mostly due to winds from the S and SE.

Modeling and verification of permafrost distribution

The permafrost distribution in the Zermatt area was investigated by different methods, including numerical modelling and verification by means of BTS-mapping and geophysical techniques. The probability of alpine permafrost occurrences was automatically calculated and mapped by using the computer programs PERMAKART (Keller, 1992) and PERMAMAP (Hoelzle, 1992; Funk and Hoelzle, 1992). PERMAKART is based upon a set of rules of thumb proposed by Haeberli (1975) and allows an estimate to be made of alpine permafrost distribution. PERMAMAP (see Figure 4) uses a statistical correlation between the potential direct solar radiation and the mean annual air temperature. Both applications have strengths and weaknesses. A digital terrain model of the Zermatt area with a resolution of 10 m was developed serving as data base for both applications. Field studies were carried out to check the calculated distributions. BTS-measurements (basal temperature of the snow cover, cp. Haeberli, 1973) were taken (Table 1) and a rock glacier inventory of the Gornergrat area was established.

Although the number of rock glaciers and BTS-data is small, some conclusions for the quality of the calculated permafrost maps can be drawn. For some locations agreement between simulated permafrost distribution and ground truthing is very good. However, the situation of certain locations is not accurately represented by the computer models. North-facing locations with increased solar radiation as well as locations characterised by intensive solar radiation such as in the Gornergrat and Trockener Steg area are not considered by PERMAKART. Although those characteristics are generally represented by PERMAMAP, the permafrost distribution of the above areas simulated by PERMAMAP does not correspond to the actual situation either, since the effects of the winter snow cover are not taken into account (Keller, 1992). According to the results of the BTS-measurements the altitude of 2,700 m

![Figure 2. Mean monthly temperatures at Zermatt (1610 m), Gornergrat (3100 m) and Kleinmatterhorn (3820 m). All three stations are within the investigation area Zermatt (see Figure 1).](image)

**Table 1: BTS-values measured in March 1996**

<table>
<thead>
<tr>
<th>Site</th>
<th>Points</th>
<th>Aspect</th>
<th>Altitude (m a.s.l.)</th>
<th>BTS (°C)</th>
<th>Permafrost</th>
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<td>7</td>
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<tr>
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Abreviations for areas: GG = Gornergrat, ST = Stockhorn, KM=Kleinmatterhorn, UR=Unterrothorn.
a.s.l. defines the lower limit of discontinuous permafrost, the altitude of 2,900 m a.s.l. the limit for continuous permafrost. Both limits are slightly higher than calculated by PERMAKART and PERMAMAP.

Periglacial geomorphology and rock glaciers

An inventory of 12 rock glaciers could be established in the Gornergrat area (see Figure 3). Three active, one inactive and four relict rock glaciers are situated on north-facing slopes. One rock glacier is active to inactive, another inactive to relict. The altitudes of the active rock glacier fronts (#1, #2, #3) run from 2,880 m to 2,950 m a.s.l.. The fronts of the relict rock glaciers (#5, #8, #9, #10) extend from 2,740 m to 2,660 m a.s.l.. One active rock glacier (T1) as well as one rock glacier characterised by several stages of activity from active to relict (T2) are situated on south-facing slopes. The front of the active rock glacier reaches down to 3,000 m a.s.l.. The upper limit of the relict stage of T2 is situated at 2,950 m a.s.l.. As indicators of discontinuous permafrost (Barsch, 1978) the active rock glaciers to the north of Gorner- Hohtälligrat determine roughly the lower boundary of discontinuous permafrost at an altitude of 2,900 m a.s.l. rising up to 3,000 m a.s.l. on south-facing slopes. (Figure 4)

Some characteristics shown by the rock glaciers seem to indicate retreat and degradation of permafrost in the Gornergrat area. The active rock glacier #2 (see Figure 5) as well as rock glacier #4 are characterised by thermokarst phenomena. Rock glacier #4 has already entered a transitional stage to inactivity. The distribution of vegetation on the sides of the active rock glaciers near the fronts may also indicate increasing ground temperatures.

Construction in permafrost terrain

GORNERGRAT RAILWAY AND KULM HOTEL

From Zermatt (1650 m a.s.l.), a railway was built up to the Gornergrat crest at 3150 m a.s.l. by 1898. Above 2600 m, it leads through discontinuous permafrost terrain (Figure 6). The formation of new permafrost in the uppermost part of the railway embankment has been described by Furrer and Fitze (1970). No serious permafrost related difficulties have arisen so far, as the embankment consists of coarse gravel and boulders.

A large hotel complex was built in 1910 at the upper end of the railway. Stability problems started after 1980 due to the installation of new 7.5 m cupolas on top of
two existing towers and heating of the tower basement. Whereas the hotel itself is built on frozen bedrock, the northern astronomical observation tower was constructed on frozen till with an active layer thickness of 2 to 3 meters.

The sinking and sliding of the tower reached values of up to 10 cm in 12 years and is monitored daily by strain gauges (Margaglio and Ripepe, 1994). Ground temperatures are measured in drillholes by King (1990; 1996). However, so far, no safety problems in the astronomical observation towers have arisen due to this instability.

An additional terrestrial survey revealed that slight movements occur in a large area of the Gornergrat mountain crest, where rock-joints may be filled with thick ice-veins, a very common phenomenon in permafrost areas.

**Funiculars in the Stockhorn Area and at the Kleinmatterhorn**

A large number of funicular stations in permafrost terrain were constructed after the Second World War: e.g., Gornergrat (3235 m), Hohtälli (3285 m), Stockhorn (3405 m), Unterrothorn (3100 m), Trockener Steg...
(2940 m), Schwarzsee (2585 m) and Kleinmatterhorn (3820 m). They usually consist of larger buildings, often in combination with mountain restaurants or service buildings. Stability is enforced mainly by basing the structure on a large concrete plate which is built deep into the blasted bedrock. However, additional care has to be taken in order to keep the subsurface frozen, even in the case of bedrock (Ulrich and King, 1993). Otherwise, difficulties are to be expected even in very high altitudes with very low permafrost temperatures.

During the summer of 1995, thick ice layers formed locally at the Kleinmatterhorn in the elevator shaft leading up to the observatory terrace and inhibited the operation of the elevator. The shaft was constructed almost 20 years ago and leads from elevation 3820 to 3870 m a.s.l. through frozen bedrock that originally had a temperature of about -10°C. Melting of permafrost is a rather uncommon phenomenon in these altitudes, where average annual temperatures of less than -7.5°C may be expected. A local inspection of the situation in April and August 1997, indicated that two factors apparently have lead to the situation: formation of a thick active layer around the small elevator building at the top, and heat transfer from the lower engine room to the summit station by air convection over a period of more than 15 years. The following remedial measures have since been applied successfully: natural ventilation of engine room and elevator shaft. The shading of the base of the elevator building by a protection wall about 1.2 m in front of the building wall has also been suggested. Thus, a thick layer of cold snow is accumulating during the winter and probably will stay throughout the following summer in the shaded interspace. The area is at least 500 m above the equilibrium line of the surrounding glaciers. In unusually warm summers, the area outside the shading wall might become snow-free and an active layer might develop, leading the ground water of the active layer away from the shaft and downslope. If the area is subject to a further climatic warming, there is still the possibility of natural cooling of the near-surface ground by circulating cold air through a system of ventilation pipes during the freezing period of 8 to 10 months.

Conclusions

The mountain area of Zermatt has a long history of development and research. Large glaciers and periglacial areas with permafrost of probably several hundred meters thickness exist due to its location in one of the highest parts of the Alps. Construction in permafrost terrain started 100 years ago. Whereas buildings constructed at the beginning of this century sometimes suffer from the melting of frozen ground (e.g. a tower built in 1910, used as astronomical observatory today), modern construction techniques are usually well adapted to the permafrost conditions. However, small disturbances of the permafrost environment may result in serious operations and maintenance difficulties.

The permafrost distribution of the area is well known through geomorphological mapping, numerical modelling, ground-survey with geophysical methods and information from construction sites. The present knowledge forms an ideal base for testing more sophisticated numerical models. However, many open questions remain, especially concerning permafrost characteristics, and consequences of possible future warming on slope stability (cf. Haeberli, 1992; 1993). Therefore, a deep drillhole is planned within the European PACE project in order to monitor the development of ground temperatures, borehole deformations and dislocations over a period of 10 to 20 years.

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References


