INFLUENCE OF MOUNTAIN PERMAFROST ON CONSTRUCTION IN THE ZUGSPITZE MOUNTAINS, BAVARIAN ALPS, GERMANY

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During construction of a cable car station, two entranceways with 8 m penetrations were blasted at 2449 m a.s.l. Approximately 10 cm wide open joints filled with frozen weathered loam and ice were discovered in the limestone. According to the high degree of cleavage and the rooflike structure of the rock profile of the Zugspitze crest, the chosen construction directed the force vector (resulting from the weight of the structure and the force of the tow-line) into the core of the mountain. The stabilizing effect of permafrost was maintained by restricting the temperature influence of the building and the direct solar impact. During construction of a railway tunnel in 1985, an ice-filled sink hole with a diameter of 15 m was penetrated at an altitude of 2560 m. The ice-body was insulated. Effects of atmospheric warming on the permafrost temperature and thickness could also be observed during construction of a new cable-way to the top of the Zugspitze.

INTRODUCTION

The widespread occurence of permafrost in the Alps is well known for countries as Switzerland (BARSCH 1977, HAEBERLI 1985), France (EVIN in KING et al. 1992), Italy (CARTON et al. 1988, BELLONI et al. 1993) and Austria (HAEBERLI & PATZELT 1982), where mountains often reach altitudes of more than 3500 m or even 4500 m a.s.l. In contrast to the mentioned regions (HAEBERLI 1992), the highest mountain in the German Alps, the Zugspitze, reaches less than 3000 m (Figure 1) and studies of active permafrost were little known until recently. This paper describes three construction sites in the Bavarian Alps and shows how the occurence of permafrost in morphologically exposed high mountain bedrock has to be accomodated with special construction techniques. The discovery of this permafrost occurence was unexpected for the leading engineers and geologists. Today the existence of permafrost is known for the area and the planning of constructions can be done accordingly thus limiting construction risks as well as financial risks.

THE CABLE CAR EIBSEE - ZUGSPITZE

The cable car system has a length of 3353 m, was constructed in 1961 and shows an altitudinal difference of 1949 m between the valley and the mountain station at 2943 m a.s.l (Figure 2). The foundation of the mountain station is located in a narrow crest formed by two differently inclined rock surfaces consisting of thickly banked and massive Wetterstein limestones (Middle Alpine Trias). This bedrock forms the northern edge of a basin structure dipping in ENE direction (strike of bedding planes: N 60 -70° E, dip: 25 to 35° towards S).

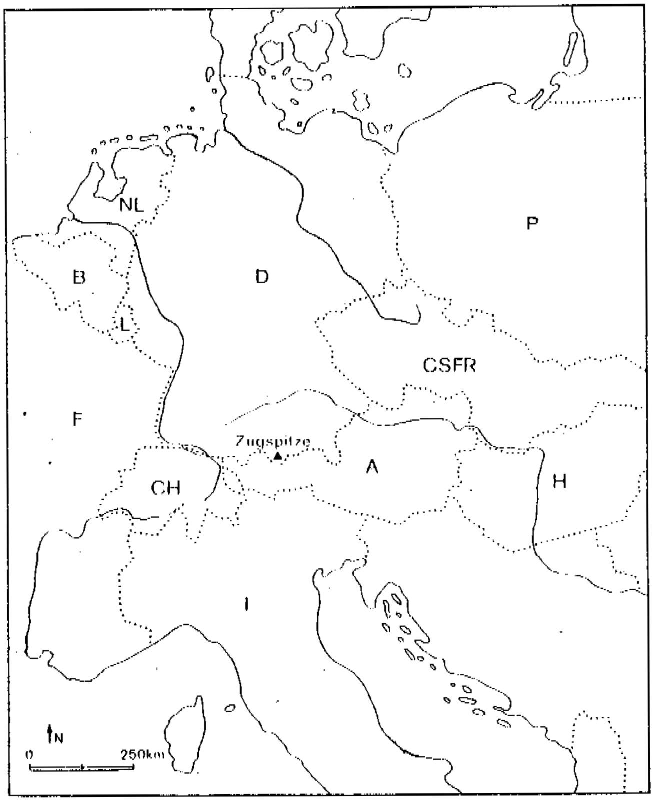

Figure 1. Location of the Zugspitze mountains.

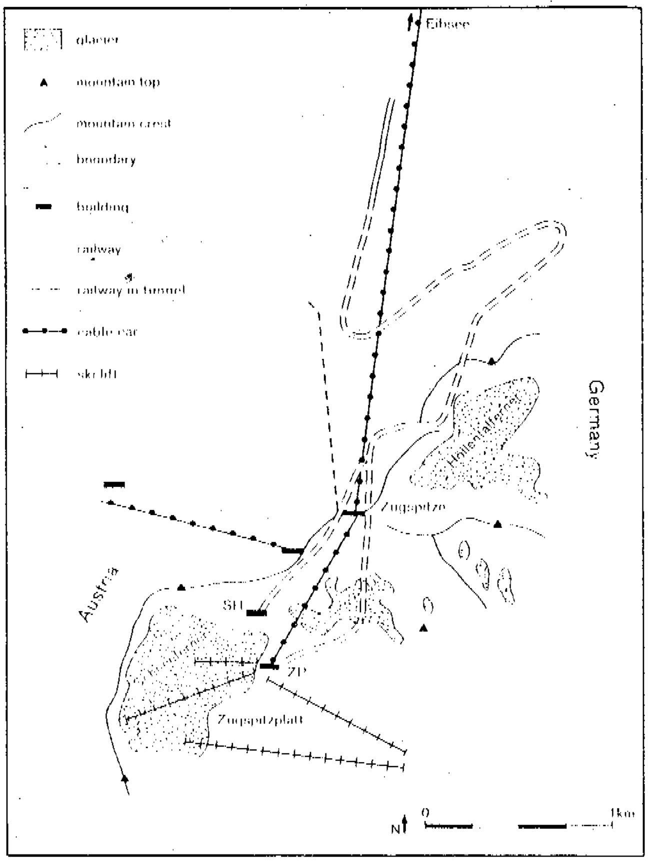

Figure 2. Location of the construction area at the mountain crest forming the border between Austria in the western half and Germany in the eastern half of the figure. Zugspitze, the highest mountain in Germany (2963 m a.s.l.) can be reached with the Eibsee cable car constructed in 1961 or via the new railway tunnel constructed in 1985 and leading to the new ski center Zugspitzplatt (ZP, 2585 m a.s.l.) and the new cable car constructed in 1991-93. The old railway tunnel leads to the Hotel Schneefernerhaus (SH, 2.665 m a.s.l.). The outlines of the glaciers (Schneeferner, Höllentalferner) display the situation in 1961; they are much smaller today.

Strong mechanical stress during orogenetic processes produced a broken rock formation, whereby strong disturbances running NNE and crosswise to the crest intensely crushed the bedrock up to the order of decimeters. Knowing well these fundamental characteristics already during the planning stade, the construction design was drawn up according to these unfavourable fractured rock conditions. The loads of a steel-portal frame construction that had to be directed into the bedrock should correspond to the weight of the bedrock broken for the entranceways, so that no additional loads had to be directed into the subsurface.

During the excavation of the 8 m deep and 7 m broad openings for the entranceways a fact was discovered that caused additional problems for the long term static safety of the construction: Perennially frozen weathered loam and up to 10 cm thick ice lenses filled the NNE-running cleavages at the foundation level: Thus the Zugspitze mountain top had to be regarded as a permafrost area and conventional rock construction techniques couldn't be used, e.g. injections of concrete for consolidation, or the application of prestressed rock anchors (cf. MÜLLER 1963, KEUSEN & HAEBERLI 1983). The functioning of these two methods was unreliable or impossible due to permafrost and ice-filled bedrock joints. The design of the foundation construction was developed in a way that avoids forces directed outwards for all possible cases of loads and all load points. The required load direction at the northerly foundations is enforced by a special support construction with a roller bearing principle similar to that used in bridge constructions. A joint bearing at the southerly foundations thus creates forces at both sides of the roof-like mountain crest that are directed towards the mountain core. These forces press together the mountain crest without e.g. prestressed rock anchors and approximatively restore the original load conditions of the mountain crest prior to the construction (cf. Fig. 3). In addition, it was decided that the foundations should furthermore be exposed to the natural atmospheric conditions in order to preserve the stabilizing effect of the permafrost. This could be realized for the northern foundation without further preventive measures, but at the southern foundation exposed to the direct solar radiation it was decided to construct in addition a sun terrasse that shaded the critical area thus evading problems by hydrology and thermal erosion (cp. KÖRNER & ULRICH 1965).

THE CABLE CAR ZUGSPITZPLATT - ZUGSPITZE MOUNTAIN TOP

With the construction of this new cable car (1991-93) from the Zugspitze mountain top towards south the availability of the ski area at the Zugspitzplatt will be facilitated. An altitudinal difference of 360 m will be surmounted with an oblique length of 1.000 meters. The top station of this new cable car is located beside the Eibsee cable car station to the west in order to allow its level connection. However, the foundation of the building was constructed in the less steeply inclined (35°) southerly slope of the Zugspitz crest in bedrock relatively little dissected by joints.

Already in an early stage, the construction of the new building could be planned according to the now known rock properties and permafrost conditions. A similar design was originally planned at the neighbouring Eibsee top station, placing the rope bollard into the northern slope. However, limited space and architectonical circumstances required that the foundation of the building had to be placed entirely on the southern slope of the mountain crest (cf. Figure 4).

During July/August 1991 the excavations for the stressing pit - through which the main load of the building would be directed into the rock subsurface - were done. The exposed layer joints below the rocksurface were filled with ice down to a depth of 3 meters. On the other

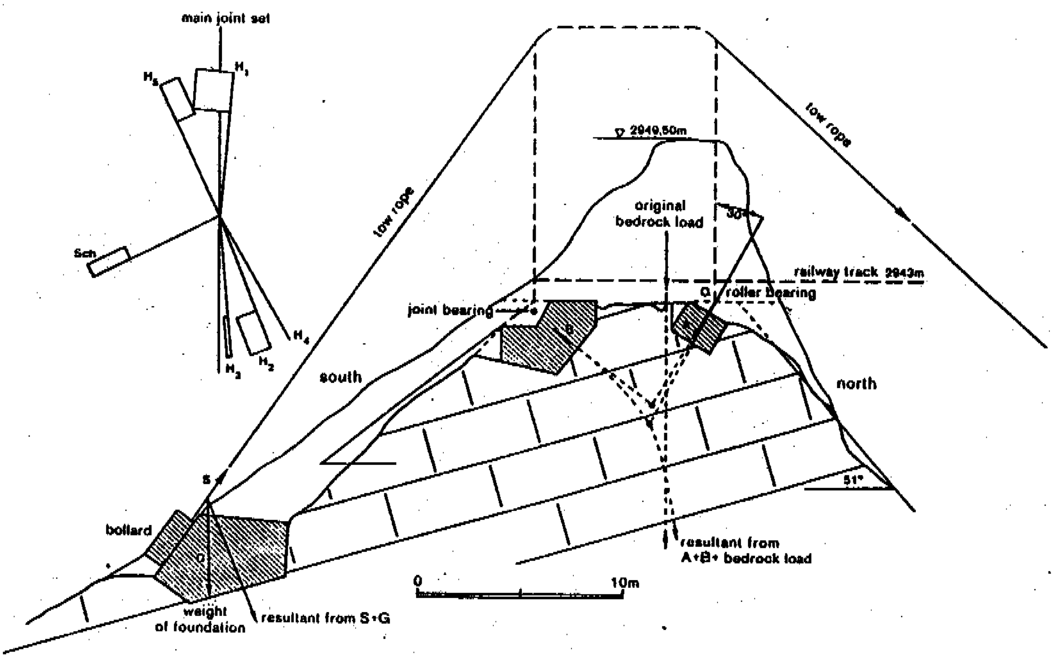

Figure 3. Section across the mountain crest with foundations of the cable car Eibsee - Zugspitze at the mountain top station.

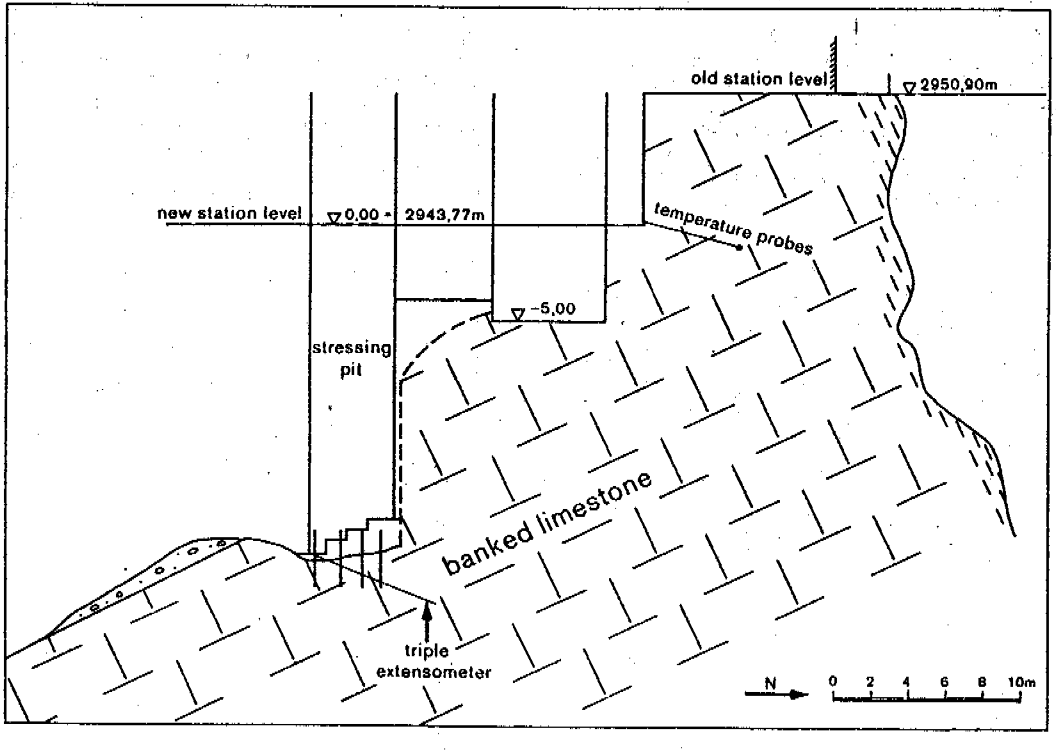

Figure 4. Foundation of the cable car Zugspitzplatt - Zugspitze at the mountain top station with locations of the triple extensometer and the probes for temperature measurements in bedrock.

hand the weathered loam in the little pronounced and NNE-running transverse disturbances was unfrozen. The layer joints had to be regarded as potential sliding planes and the excavations for the stressing pit were therefore deepened down to depths where the occurence of open, ice-filled joints was highly improbable. In addition an extensive plugging (one three-meter rock bolt per m^2) between the foundation concrete and the bedrock was applied in order to increase the shear stability. A "triple extensometer" with lengths of 5, 10 and 15 meters for the observation of the bedrock below the stressing pit was also installed, because the stability could not be evaluated clearly and because the construction site was extremly exposed. The installation allows to judge during the construction the increasing influence of the load to the subsurface. According to the new data obtained at the southern slope of the Zugspitze mountain top, the use of rock anchors in the bottom zone of the stressing pit would be possible, because the extensometer drilling didn't hint to the occurence of deep reaching permafrost. At the end of the year 1992, a drilling directed towards the north wall will be done in order to install thermistors to monitor rock temperatures.

The construction of the new cable car required the demolition of the sun terrasse at the mountain top station of the Eibsee funicular. There, it could be observed, that extensive ground ice had formed in the excavation material since its deposition about 30 years ago. The ice formation continued into the open joints of the bedrock. As expected, the (tritium) dating of the ice gave a very young age (after 1965).

Actual formation of permafrost and ground ice at this site is well understandable at this shaded site with little ventilation and evaporation, and may also be expected when considering the air temperatures (Figure 5) measured at the nearby official weather station of the German Weather Service (DWD). The ten year mean temperatures show a slight increase from -5.25° in the first decade of this century to -4.9° C in the sixties and seventies and to -4.6° C during the last ten years. According to KING (1983, 1986, 1990) and others, this means that permafrost occurences are probably quite widespread here, and that a considerable permafrost thickness may be expected at least in slopes exposed towards north.

A comparison of the precipitation values between the first 30 years of this century and the period 1961 to 1989 reveals also remarkable results: The precipitation total has significantly increased from 1332 mm per year to 2009 mm per year (Figure 6). During these 90 years the glacier tongue at the Zugspitzplatt has receded continuously and is located today at 2.570 m a.s.l. A detailed climatological analysis shows, that especially winter temperatures have increased in the fifties and seventies, and that quite a considerable amount of precipitation has probably fallen as rain instead of snow, providing an explanation for the continuous negative mass balance and glacier retreat.

THE CONSTRUCTION OF A NEW RAILWAY TUNNEL TO THE ZUGSPITZPLATT

This rack-railway, originally constructed in the year 1930, leads from Garmisch-Patenkirchen (994 m a.s.l.) to the Zugspitze Hotel Schneefernerhaus at 2665 m a.s.l.. An additional railway branch leading to the ski center at the Zugspitzplatt and with a length of 800 m was added in the year 1985. The new tunnel was explored in an area with little roof cover by 5 boreholes. It was discovered then, that below up to 15 m morainic material there is primarily solid limestone bedrock. On the other hand it was known that karst features occur in the basin-like "Zugspitzplatt" (e.g. sink holes and ponors), which were sometimes filled with ice. It was however by pure hazard that the tunneling after only about 100 meters entered an area with massive ice over its whole

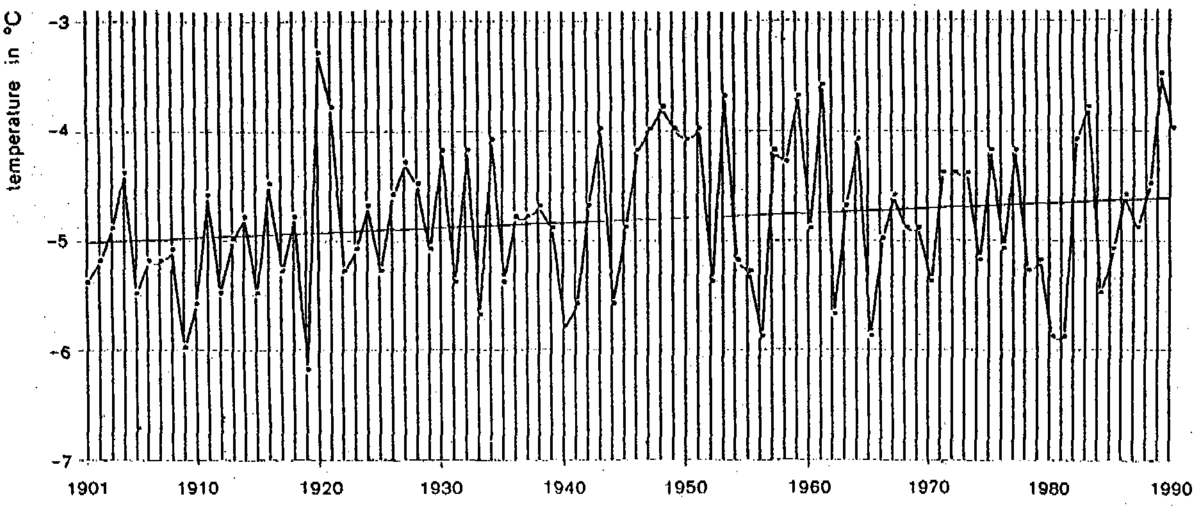

Figure 5. Mean annual air temperatures 1901 to 1990 and linear regression at Zugspitze, 2960 m a.s.l.

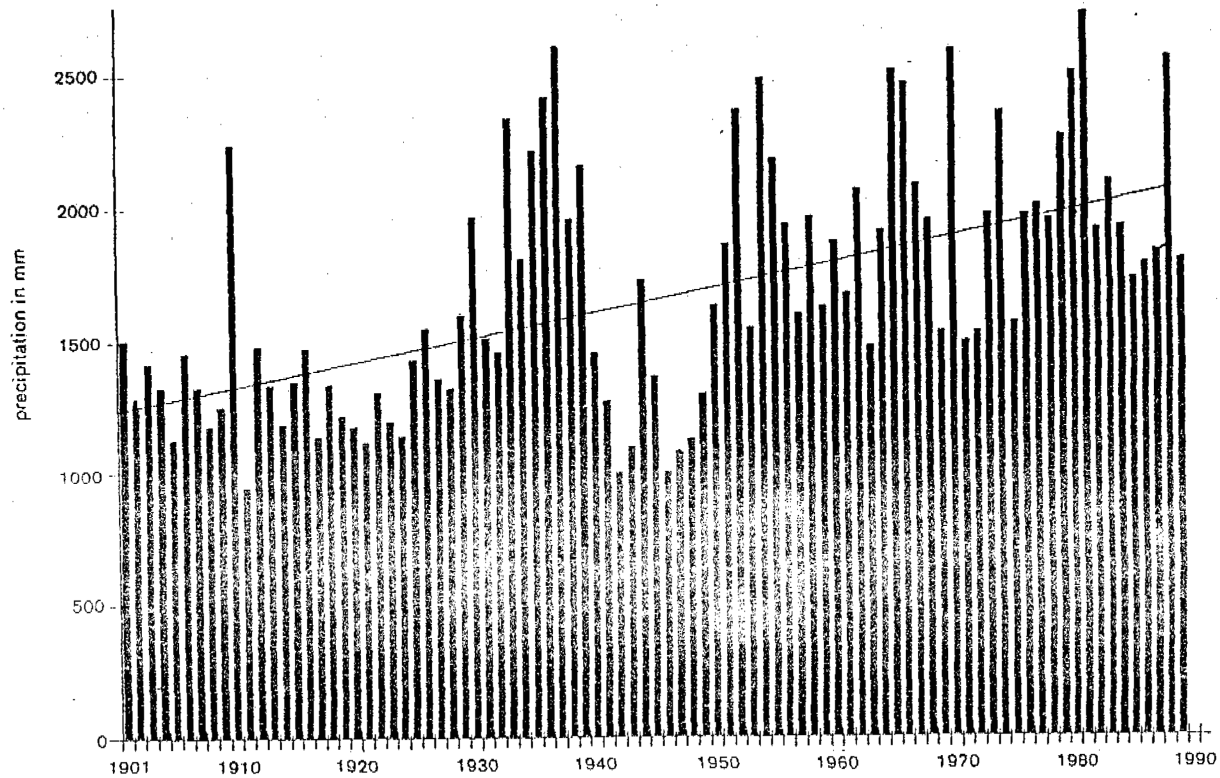

Figure 6. Annual precipitation 1901 to 1990 at Zugspitze, 2960 m a.s.l., and linear regression line.

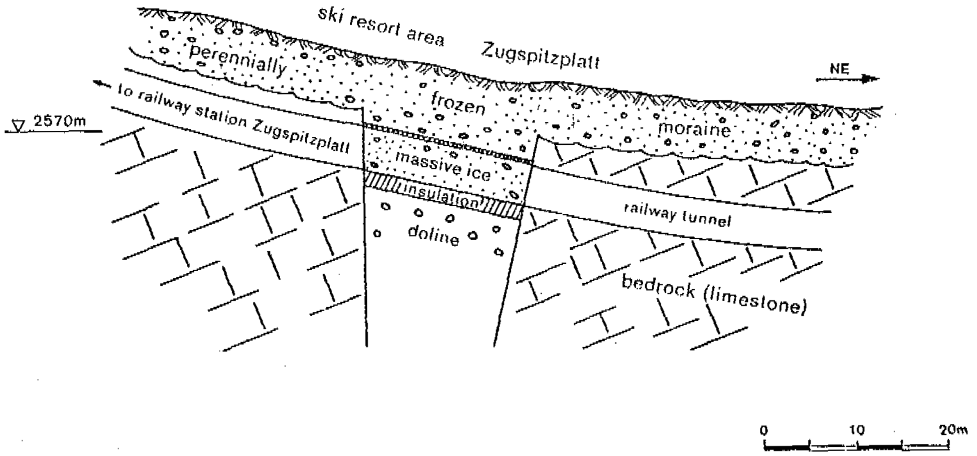

Figure 7. Tunnel track in the area with the ice-filled doline. The moraine cover is perennially frozen and the frozen debris shows thick ice lenses and massive ice. The tunnel track entered an area mainly with massive ice. The railway track was well insulated (cf. text).

diameter. Rock particles marked a 45° stratification at its left hand side, flattening towards the right hand side. The tunneling undoubtedly established the fact that an ice-filled sink hole was hit, a massive ice body of unknown size. Test borings then revealed ice for a distance of 19 meters (cp. Figure 7).

The foundation for the rack-railway track, extremely sensitive to settlement, required intensive investigations into the problem of heat exchange between the heated tunnel air and the ice. It had to be reliably determined that melting of the ice and future thaw settlement of the railway track could be excluded. Assuming an air temperature of +6° C and an ice temperature of -1.5° C, heat flow calculations revealed a progressive melting of the ice along the whole tunnel soffit. In order to avoid this, the use of insulation material below the heavily loaded railway track was required as follows:

- 1 m thick gravel bearing layer on
- 0.1 m damming layer of foam glass (i.e. pure glass based on aluminum and silicon, acid resistant, compressive strength 0.5 N/mm^2),
- 0.3 m gravel bed with sleepers.

The tunnel wall was insulated with a 0.3 m thick layer of shotcrete on the ice and 0.1 m thick slabs of rockwool at the inner surface of the tunnel. The temperature in the massive ice body is continuously recorded at 6 sites. The ice temperatures just behind the tunnel cover show mean annual values of -0.5° C (measured over a period of 6 years). Until now, there was no detrimental influence of the tunnel statics and the railway track due to melting processes.

A final remark concerns the origin and age of the ice: The tunnel area investigated was still ice covered in 1856 and became ice-free after about 1892 (FINSTERWALDER 1950). The karst morphology of the Zugspitze area have been formed between the Pliocene and the Lower Pleistocene. The weathering loams at the Zugspitze mountain top originate from an older cover above the actual mountain crest and are not a weathering product of the limestone ("Wettersteinkalk").

CONCLUSIONS

Construction experience shows that permafrost in bedrock plays only a minor role concerning the stability, because the cleavage volume filled with ice is limited. The described construction measures have shown, that a critical examination of the structure stability in areas of mountain permafrost has to consider primarily the joint set of the rock (set-up and degree of separation) and the morphological circumstances of the construction site. However, permafrost may have a long lasting stabilizing effect, if at least partly cohesive joint fillings occur, that would have negative effects for the shearing strength of unfrozen rock.

According to the actual climatic trend, a reduction of the permafrost extent may be expected, and instruments recording the temperature development and the rock compression have been installed therefore at the foundation level. If the observations point out, that the conserving effect of the permafrost diminishes in course of time, a stepwise replacement by grout injections and tie-rods is intended.

In contrast to bedrock, ice in frozen debris (moraines, slope material) often forms the effective matrix and therefore strongly influences the load capacity and shear strength with ice temperatures of about -3° C. In bedrock and frozen debris, some difficulties may be encountered with the corresponding techniques described in this paper.

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