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RECENT GEOPHYSICAL INVESTIGATIONS AT A HIGH ALPINE PERMAFROST CONSTRUCTION SITE IN SWITZERLAND

Matthias Wegmann[1], Hans-Rudolf Keusen[2]

1. *Laboratory of Hydraulics, Hydrology and Glaciology, ETH-Zurich, Switzerland*
e-mail: wegmann@vaw.baum.ethz.ch

2. *Geotest AG, Consulting Geologists and Engineers, Zollikofen Bern, Switzerland*

Abstract

The construction work for the extension of the Sphinx observatory (3,550 m a.s.l.) at Jungfraujoch, Switzerland, was a geotechnical challenge with respect to alpine rock permafrost. In view of possible destabilisation, precise monitoring of rock temperatures and deformation around a 100 metre long elevator shaft with a diameter of 6.5 metres was necessary. Inverse correlation between temperature and deformation related to freezing and thawing was observed, as well as irreversible deformation as a consequence of the construction activities. To prevent further thawing, the elevator shaft is now actively cooled. The temperature history is modelled in a two dimensional north-south cross section through the rock ridge at Sphinx. The calculated permafrost thickness is more than 200 metres and the active layer is approximately 3 metres thick.

Introduction

Europe's highest railway station Jungfraujoch (3,500 m a.s.l.) is situated at the head of central Europe's largest glacier, Grosser Aletschgletscher. The railway construction started more than a century ago and reached Jungfraujoch in 1912. A scientific station, the Sphinx observatory and a hotel were constructed in the following two decades. In October 1972 the hotel caught fire and burned down completely. New tourist facilities were opened in 1987 and the railway terminal was enlarged between 1990 and 1991. The most recent building activity was the extension of the Sphinx observatory, which is situated in continuous alpine permafrost.

Technical difficulties associated with construction activities in high Alpine permafrost regions are well known and have been described elsewhere (Haeberli et al.,1979; Keusen and Haeberli, 1983; Haeberli, 1992; Ulrich and King, 1993, Haeberli et al., 1997). Alpine rock permafrost is widespread at Jungfraujoch. Experiences from former building activities (Rieder and Keusen, 1980; Keusen and Amiguet, 1987) could therefore be taken into account during the planning and construction of the extension of the Jungfraujoch Sphinx observatory. This paper describes the permafrost and construction monitoring scheme at the Sphinx ridge, and presents and discusses results from measurements and model calculations.

Extension of sphinx observatory

The Sphinx observatory (Figure 1) is located on a narrow, rock ridge 120 metres above the railway station Jungfraujoch. Originally the access to the observatory was a small elevator built in 1937. The capacity of this elevator became too small for the growing number of visitors. For this reason an extension of the Sphinx with a covered observation platform and a twin elevator was built between 1993 and 1996 (Steiner et al., 1996).

The rock of the Sphinx ridge consists of three lithologies (Figure 2). The top consists of a chlorite-sericite-gneiss (Innertkirchen-Lauterbrunner Kristallin) followed by inter-folded (Alpine orogenesis) foliated limestones (Jurassic Malm). The limestones are underlain by granitic gneisses which are part of the Central Aare Massif . These lithologies are crossed by three main systems of discontinuities. The schistosity dips towards SSW (Az. 200°) and is irregularly and undulating (dip 15° to 20°) with wavelengths in the order of decimetres. The two main joint systems K1 and K2 are responsible for the shape of the whole Sphinx ridge. The predominant joint system K1 (Az. 135°, dip 90°) is persistent and the spacing of the joints is between 1 and 4 metres. Open fissures of K1 are partly ice-filled. The system K2 (Az. 225°, dip 65°) is not persistent and subordinate.

The excavation of the new 95 metre long elevator shaft with a diameter of 6.5 metre was especially challenging. In view of a possible destabilisation of the sur-

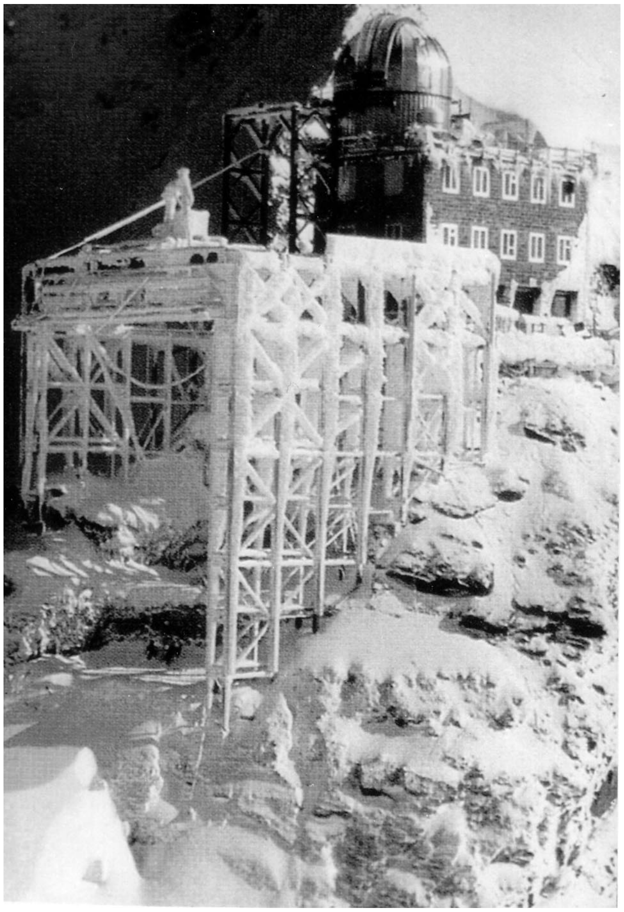

Figure 1. The old Sphinx observatory and the construction site in winter 1993/94. To enable construction work throughout the whole year a protection shed was erected after excavating a total volume of 1,000 m^3 of rock material.

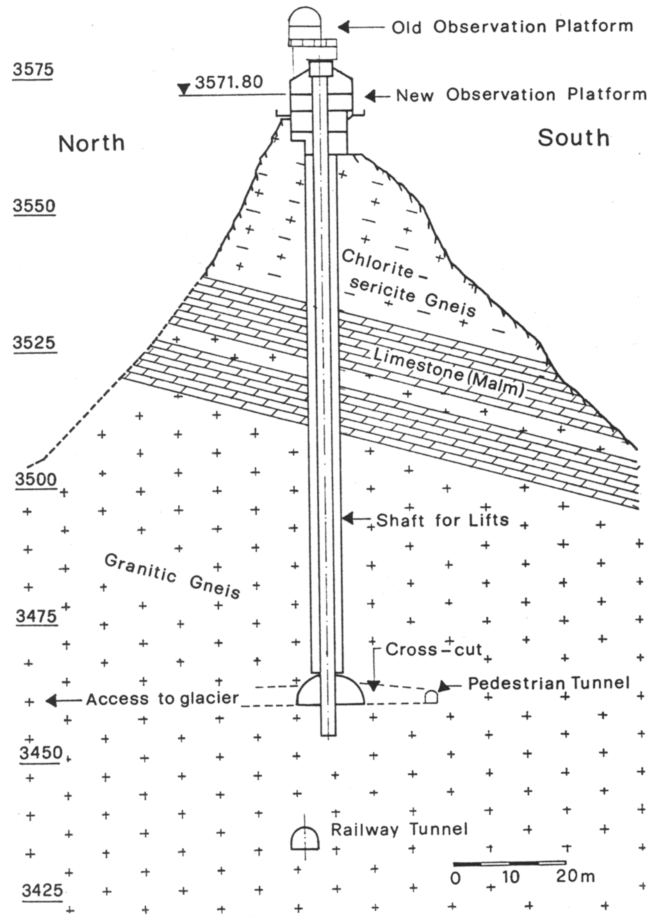

Figure 2. Geological cross section north-south (modified from Steiner et al., 1996).

rounding rock body, exact monitoring of rock deformations and temperatures became particularly important around this shaft.

Monitoring scheme

The climatic conditions at Jungfraujoch are recorded by an automatic meteorological station at the Sphinx observatory. The mean annual air temperatures are approximately -8°C. Due to the presence of permafrost as well as complex loading and bedrock conditions an analytical design could not be carried out. Thus, it was necessary to apply an observational procedure to monitor the behaviour of the rock ridge (Figure 3).

Several years before construction an 85 metre deep, borehole (Rb88.01) was drilled and equipped with thermistors, a slope indicator casing, as well as an incremental extensometer. These sensors were read manually every week.

Prior to construction four boreholes (SB1-4) were drilled from the basement of the existing building with different orientations and dips in relation to the ridge surface. These boreholes were equipped with multipoint extensometers (E1-E4) and thermocouples (T1-T4).

During and after the excavation work on the ridge surface, the geological structures were mapped. Two main joint systems were observed and some cracks were ice-filled. These observations were then used for extending the monitoring scheme with deformation (E10-E13) and temperature (T11-T13) sensors in an other series of boreholes (SB10-13, Rb94.01) below the new excavation and around the new shafts.

The different sensors were linked to a datalogger and the readings were transmitted via telephone modem to the office.

Measurements

Temperature History

The construction history is reflected in the different measurements. The temperature records of the six thermistors installed in the vertical 85 metre deep borehole (Rb~88.01) are illustrated in Figure 4. Before winter 1993 the temperature records show a heat conductive behaviour, with largest amplitudes near the surface and an amplitude decrease and phase shift with depth. The thermistor at a depth of 50 metres was close to the depth of the zero annual amplitude and close to the permafrost base.

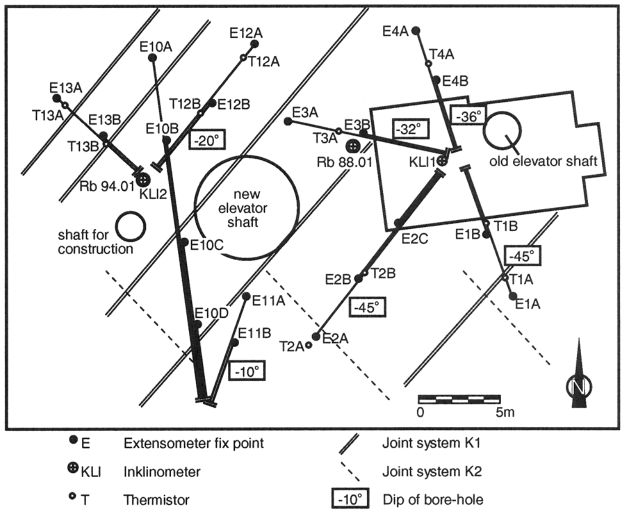

Figure 3. Layout of construction and permafrost monitoring sites (modified from Steiner et al., 1996).

The excavation work on the ridge surface began in spring 1994 and is reflected in the sudden temperature increase at 5 and 10 metres depth. In autumn 1994, the final excavation of the elevator shaft and the concreting of the lining was performed. During concreting the temperatures in the elevator shaft were constantly between 12° to 15°C. In the parallel borehole 4 metres away, these operations are illustrated by a sudden increase of all temperatures above 0°C. As changes in the permafrost distribution might lead to rock destabilisation, a cooling system with two ventilation spaces was installed in the new elevator shaft. The temperatures in the upper 45 metres of the shaft are now cooled to approximately -1°C.

Thermo-Mechanical Behaviour

Boreholes SB1-4 and SB10-13 are equipped with thermistors and extensometers. The measured displacement (Δl) of each extensometer rod is normalised and expressed as strain ($\varepsilon = \Delta l / l_0$). These measurements allow an interpretation of temperature, freezing (and

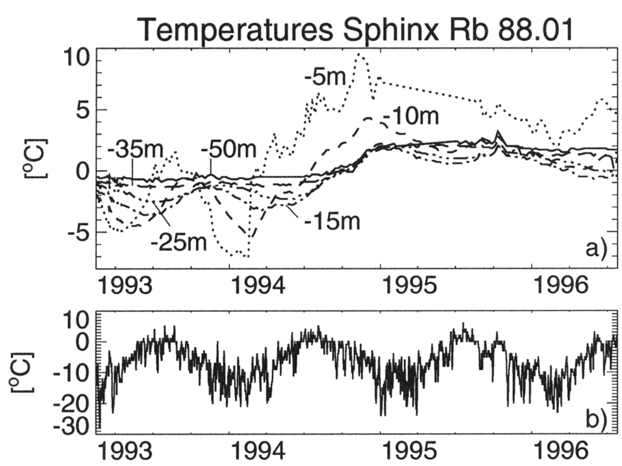

Figure 4. (a) Temperature history in borehole Rb 88.01 (Figure 3). (b) Smoothed air temperatures at Sphinx observatory.

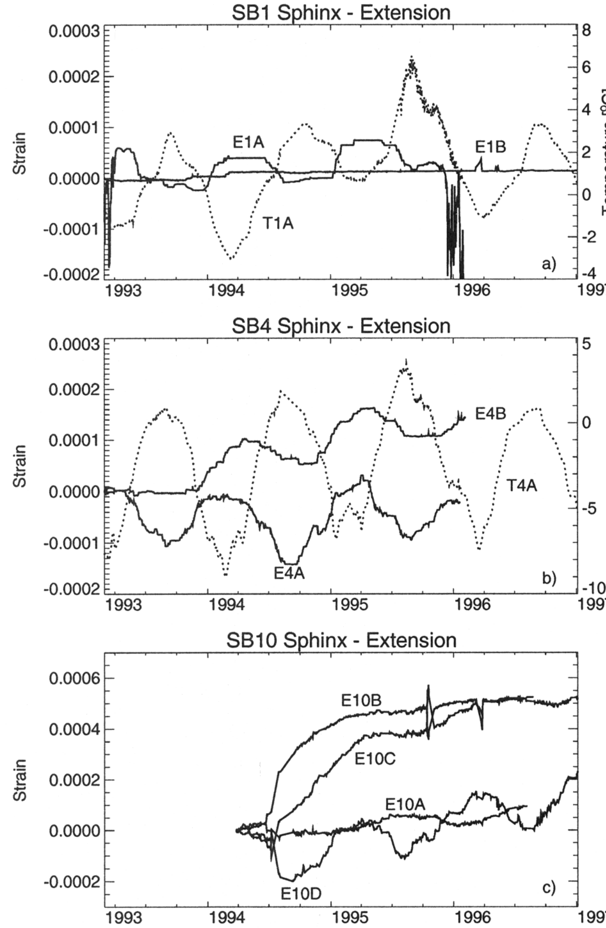

Figure 5. Inversely related temperature-strain behaviour: (a) south side and (b) north side of Sphinx ridge. (c) Irreversible strains due to elevator excavation with thawing in rock fissures (locations see Figure 3)

thawing) and construction related deformations. The boreholes from the basement of the old observatory (SB1-4) are less influenced by the construction activities, than the ones below the new building (SB10-13). In this paper we present typical results from strain and temperature measurements measured in boreholes SB1, SB4 and SB10. The depths at which the thermistors are installed or for which the strain measurements are representative, are measured from the head of the boreholes and not from the surface of the ridge.

Extensometer E1A and E1B (Figure 5a) measure strains towards the south side of the ridge. While E1B shows hardly any strain, E1A which is closer to the surface shows annual cyclical deformation. Unfortunately a defect ended the measurements at E1A in winter 1996/97. The strain amplitudes of E1A are on the order of $5 \cdot 10^{-5}$. The temperature record (T1A), measured at a depth of 9 metres is inversely correlated with the strain at the same depth range (E1B). The mean annual rock temperature at T1A is close to 0°C.

At the colder north side of the Sphinx ridge, the mean annual rock temperature (T4) is about -4°C (Figure 5b).

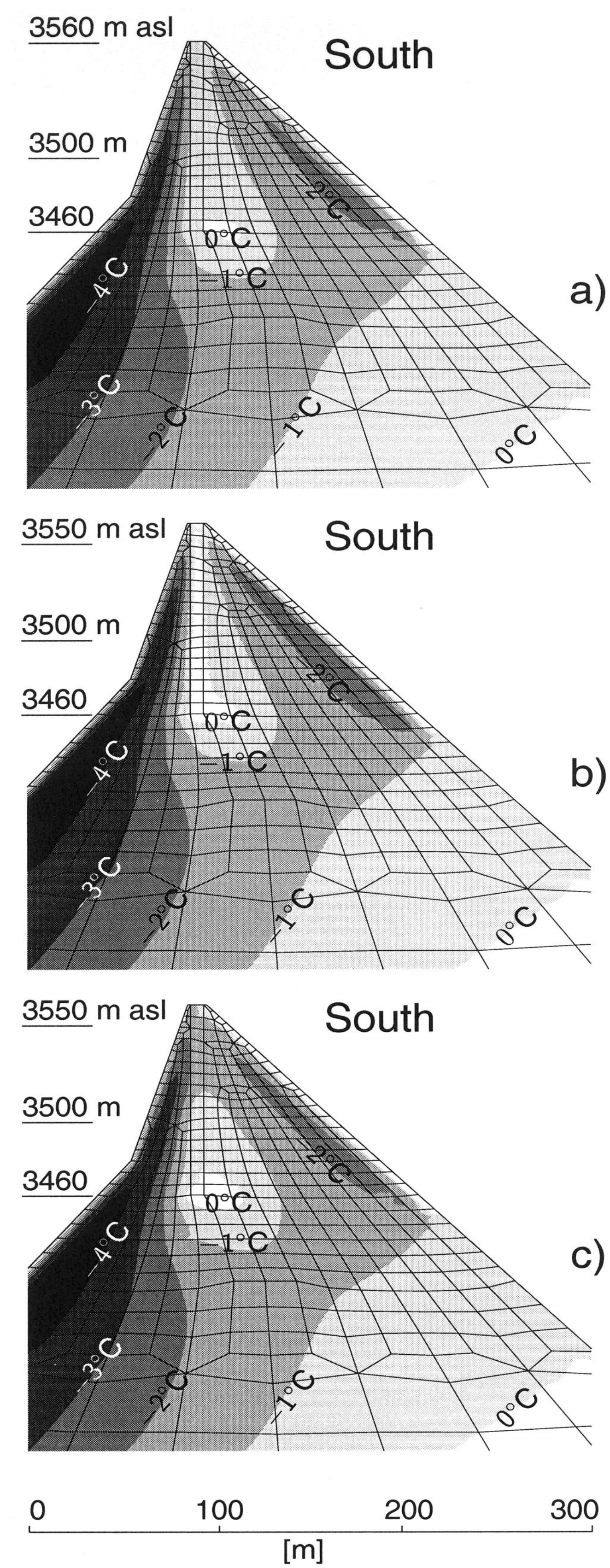

Figure 6. Numerically modelled temperature distribution in a simplified north-south cross-section through Sphinx ridge. Isotherms with an interval of 1°C are marked by the change in the shading intensity; (a) represents the temperature distribution before construction start, (b) at the end of the elevator construction and (c) with the cooled elevator shaft.

The strain behaviour on the north side is again inversely correlated with annual temperature variations. Extensometer E4A, which is closer to the ridge surface, shows reversible deformations, as at extensometer E1A. At extensometer E4B, the cyclical strains are superimposed on irreversible deformation. This irreversible opening of fissures in the first 5.5 metres of borehole SB4 can be related to the construction activity.

The inversely correlated behaviour of strain and temperatures in boreholes SB1 and SB4 can only be explained by seasonal freezing of moisture and thawing in rock fissures. Deformation related to freezing are also observed at sustained sub-zero temperatures. Due to the construction work (concreting), the bedrock is locally warmed up and the ice in joint system K1 thaws. The water is free to migrate in the fissure's direction. It is probable that the irreversible opening of K2 joints at extensometer E4B is related to such an additional water supply.

Borehole SB10 crosses the sphinx ridge close to the new elevator shaft. Two originally ice-filled joints along the new elevator axis are responsible for large strains (5.10-4) during the excavation work for the shafts (Figure 5c, E10B and E10C). Based on these observations, the dimension of the reinforced foundation slab was increased. These large strains ended in spring 1995.

Model calculations

In a simplified cross section of the Sphinx ridge, different probable temperature distributions were numerically calculated using the general-purpose finite element program package MARC/Mentat (MARC, 1995).

Along the lower boundary of the model (0 m a.s.l.) a constant vertical heat flux of 60 mW m^{-2} was applied (Medici and Rybach, 1995), while on the surface, time dependent temperature histories were used. On the south side of the Sphinx ridge the glacier covers the bedrock up to an altitude of 3450 m a.s.l. The temperatures at the glacier bed were fixed to 0°C. The temperature in the railway tunnel and in the old tunnel access to the glacier were prescribed as 0°C and 1.5°C, respectively. Annual sinusoidal temperature fluctuations and different elevation corrections for the north and south side were applied at the ridge surface. The effects of freezing and thawing of moisture on the temperature field were simulated with the use of an effective heat capacity. No mass transfer processes were allowed and we chose isotropic rock material properties.

Detailed strain and temperature measurements in two 20 metre deep boreholes in the thermally undisturbed bedrock at the nearby east ridge of Jungfrau were used to select appropriate material and freezing properties

(VAW, unpublished data). In these similar lithologies the strain behaviour is inversely correlated with the annual temperature wave. The water freezes in the temperature range of -0.3° to -0.4°C ("zero curtain"). The local latent heat consumption has been calculated form the temperature record (Pfeffer and Humphrey, 1996). The total amount of water which freezes every year, is equal to a rock moisture content of 3%. The volume expansion during freezing has the capacity to deform the bedrock. Approximately 10% of the theoretical freezing expansion can be observed in the strain measurements at Jungfrau east ridge.

The thermal model calculations for the Sphinx ridge start with a steady-state temperature distribution in spring 1992. Afterwards, the transient heat transfer analysis begins. The calculated temperature field of autumn 1992 (Figure 6a) suggests that the active layer on the south facing side of the ridge is approximately 3 metres thick. The thermal history, with the elevator shaft construction is then analysed. In Figure 6b, the temperature distribution at the end of the elevator shaft construction is illustrated. Since the upper 45 metres of the elevator shaft is now cooled down to -1°C, we calculated the new steady-state temperature distribution within the sphinx ridge (Figure 6c).

In a further step, the thermal model calculations were used to analyse the strain measurements. In a thermo-mechanical coupled model, the annual deformation in the thermally undisturbed bedrock were simulated. The calculated strain is of the same order of magnitude as the measurements in the boreholes (before construction activity).

Conclusions

Construction experience shows that high precision, automated temperature and deformation monitoring is very useful during and after building activities in rock permafrost. The small amount of frozen ground water in rock fissures is very susceptible to temperature disturbance. The thawing of ice changed the deformation pattern and the stability situation immediately. In undisturbed bedrock, inverse relationships between displacements and temperature were observed.

Model calculations demonstrate that the permafrost thickness at Jungfraujoch probably exceeds 200 metres. The influence of the tunnels and of the construction activities on the ground thermal regime are further demonstrated.

Acknowledgments

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