

SURFACE MOVEMENT AND INTERNAL DEFORMATION OF ICE-ROCK MIXTURES WITHIN ROCK GLACIERS AT PONTRESINA-SCHAFBERG, UPPER ENGADIN, SWITZERLAND

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Abstract

Two boreholes were drilled into rock glacier permafrost on the Pontresina-Schafberg, Upper Engadin, Eastern Swiss Alps. The two permafrost bodies differ in temperature distribution, ice and debris content as well as surface and bedrock topography. The borehole deformation was monitored with a slope indicator (horizontal deformation) and with magnetic rings (vertical deformation). The average surface velocities observed are 3 cm/a at borehole 1 and 1 cm/a at borehole 2. The flow velocities appear to be correlated to the ground temperatures. In addition, photogrammetric investigation reveals the surface velocity field for the period between 1971 to 1991. All these measurements are in close accordance with each other and open new perspectives for the ongoing research at this site.

Introduction

Ground ice is a common occurrence in periglacial regions of high mountain environments which are characterized by low temperatures and steep slopes. Creep of ice-supersaturated permafrost is often observed. The typically resulting morphological landform is termed a rock glacier (Haeberli, 1985). With increasing use of cold mountain areas for tourism, strategic purposes and in connection with communication networks and

hydroelectricity production, improved knowledge of permafrost creep is of fundamental importance during the planning stages of any construction activity in these high Alpine environments (Haeberli, 1992). However, creeping permafrost not only poses geotechnical challenges, but also has to be considered in connection with protection for, and mitigation of, natural hazards as debris is continuously transported to potential starting zones of debris flows (Haeberli et al., 1990; Zimmermann, 1990). Measurements of flow velocity fields based on photogrammetric analysis, as well as

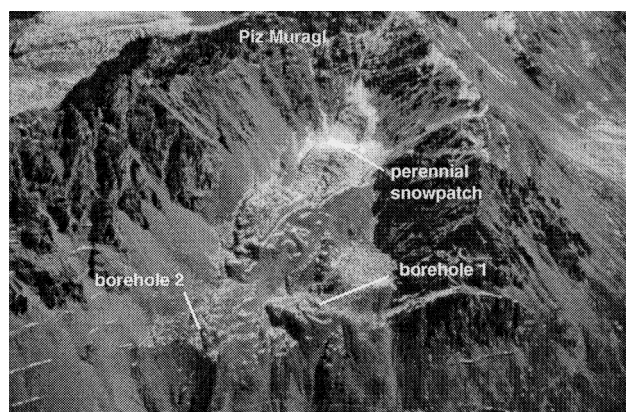


Figure 1. Overview of the study site at Pontresina-Schafberg, Upper Engadin, Switzerland.

information from borehole investigations such as deformation measurements or geophysical soundings, allow a better understanding of the formation, development and dynamics of high mountain permafrost creep.

The number of field studies with direct observations in boreholes is limited, especially on rock glaciers. Such boreholes, which allow in situ observations, are in general very expensive because of difficult access and the requirements of extensive installations (Savigny and Morgenstern, 1986a; 1986b; Dallimore et al., 1995; 1996). In contrast, a number of extensive laboratory and theoretical studies on the creep behaviour of frozen ground exist (Savigny and Morgenstern, 1986c; Loewenherz et al., 1989; Ladanyi et al., 1995; Wagner, 1996).

In autumn 1990, two boreholes were drilled in the avalanche protection area of Pontresina-Schafberg, Swiss Alps. They form part of a recently established Swiss mountain permafrost monitoring network (Haeberli et al., 1993). Long-term monitoring of internal creep behaviour was carried out in combination with a photogrammetrical survey study in the same area. This paper presents preliminary results and qualitative interpretations from measurements of borehole deformation and photogrammetrically derived surface velocities.

Investigated area and drill sites

Pontresina-Schafberg area is situated in the Upper Engadin, Switzerland (Figure 1). Permafrost drilling was carried out in connection with an avalanche and debris flow protection research project (VAW, 1988; 1990; 1991; Stoffel, 1995). The two drill sites were carefully chosen after extensive geophysical investigations (Vonder Mühll, 1993). Borehole 1 (BH 1) is 67 m deep with bedrock located at a depth of 16 m. Borehole 2 (BH 2) leads to a depth of 37 m and bedrock was encountered at 30 m. The mean surface temperatures estimated from the ground temperature gradient observed in the two boreholes are -1.7°C and -1.0°C respectively (Vonder Mühll and Holub, 1992). Geophysical borehole

logging in BH 1 identified the first 10 m as a layer with a 30% ice content by volume. In the next 5 m, ice content was up to 80% by volume. In BH 2, geophysical borehole logging was only performed in the uppermost 12 m (Vonder Mühll and Holub, 1992).

Methods

BOREHOLE DEFORMATION MEASUREMENTS

The two boreholes were cased with plastic tubes to monitor the horizontal deformation using a slope inclinometer and vertical deformation using magnetic rings. At both sites, the plastic tubes are fixed in stable bedrock at the bottom of the holes. The plastic tubes measure 17 m at BH 1 and 38 m at BH 2.

For the measurements of borehole inclination, the SINCO Digitilt system was selected as most suitable. The Digitilt system uses null-balance accelerometers as sensing elements. For each measurement, the inclinometer probe was set to the lowest reading depth for at least 5 to 10 minutes to allow for the sensor to stabilize. The probe was then removed and readings were taken every 0.608 m. This procedure was repeated two to three times for each measurement. After Savigny and Morgenstern (1986b) and Dallimore et al. (1996), the accuracy of this instrument is very high and better than the manufacturer's specifications. An error assessment of all measurements was performed and provided a mean error in each direction, A and B, integrated from the bottom to the surface, of less than 1 cm at the top of the slope tube.

The magnetic rings were installed outside of the inclinometer plastic casings, separated by intervals of 3 to 5 m. They are measured with the help of a magnetic sounding lead. During a single series of measurements, the upper and lower edges of a magnetic ring are measured three times with an accuracy of ± 1 mm or better.

PHOTOGRAMMETRIC MEASUREMENTS

Aerophotogrammetric determination of digital terrain models (DTM) and subsequent comparison of multi-temporal DTMs is an effective and well-established technique to precisely define terrain surfaces and their changes in elevation with time. The method uses monotemporal stereo models, composed of at least two overlapping photographs, which are taken from different positions.

Changes in surface elevations on rock-glaciers are the result of changes in mass balance and three-dimensional flow regime. Thus, determination of surface displacements in three dimensions helps to create a better understanding of these processes. The analytical photogrammetric method presented here uses multitemporal stereo models composed from aerial photographs

taken at different times and from different positions (photos are from the Federal topographical survey). This procedure is called monoplottting. An image point A1 at time t2 corresponds to an image point A2 at time t1 using the stereoscopic overlap. The operator of the analytical plotter thereby compensates for the terrain movement which has occurred between t1 and t2 by displacing one image while simultaneously looking at the multitemporal photographs. This simultaneous and stereoscopic observation supports the identification of corresponding points, improves the accuracy of the measurements and, additionally, indicates whether a local displacement significantly reflects its surrounding terrain. With the help of this method, the spatial displacements of surface points can be deduced area-wide. The surface terrain over which the velocity field is to be determined has to fulfil two basic requirements: the displacements must be larger than the accuracy of the method to obtain significant results and secondly, terrain deformation or destruction between the times of photography (e.g., caused by thawing or terrain slip) should not prohibit the identification of corresponding points. Both requirements can be satisfied by choosing a suitable time interval between the photo missions. The photogrammetric technique described here works especially well for determining the creep of permafrost surfaces but is also suitable for observing glacier flow and slope movements. Maximum accuracy of the method, as deduced by repeating measurements using independent multitemporal stereo models and by comparing the results with geodetic stake measurements, is estimated to be about 30 micrometer in image scale. The photogrammetric analysis was performed with an analytical plotter (Kern DSR 15-18).

Results

BOREHOLE DEFORMATION

The first measurements in both boreholes were carried out in November 1990. In BH 1, the total displacement in xyz-directions at the surface reached 22 cm between November 1990 and July 1997. At the beginning of the first year, the plastic tubes in BH 1 (and probably also in BH 2) were not in full contact with bedrock. Figure 2 reveals a tipping movement of around 2 cm in the first measurement year in the lowest part of BH 1. The annual surface flow velocities calculated from the displacement measurements are in a range of 2-4 cm/a (Figure 3). The main deformation in this borehole occurs at a depth of 10 to 15 m. Figure 4 shows the flow direction as a function of depth along the BH 1 axis. It is noted that the flow direction at a depth of 11 m is rotated by about 20° with respect to that at the surface. The calculated vertical annual velocities range from 5 to 15 mm/a.

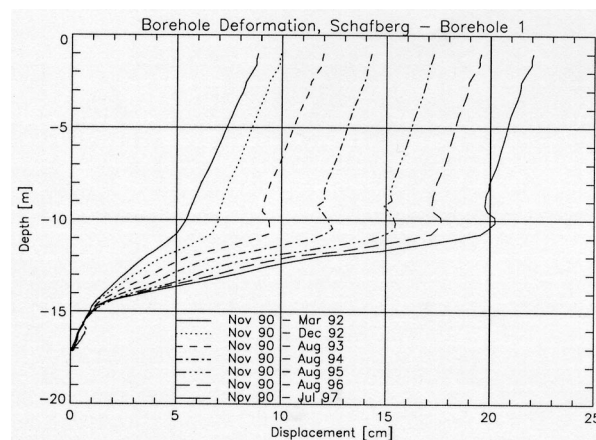


Figure 2. Displacement in xyz-direction at BH 1 calculated from slope and magnetic ring measurements.

BH 2 shows much less deformation than BH 1. The annual surface velocities at this site are around 1 cm/a. Here, the main deformation occurs at a depth of 25 m.

PHOTOGRAMMETRY

The measured surface displacements vary in this area between 40 and 60 cm during the time period 1971-1991. The average annual surface velocities calculated from the surface displacements are therefore in a range of 2-3 cm/a for this area (Figure 5). At most places, the rates of changes in surface elevations are smaller than 2 cm/a (Kääb, 1996). These values are marginally significant and should be interpreted only qualitatively. To improve the accuracy of the analysis, six independent digital terrain models and four multitemporal stereo models were measured. The mean errors resulting from this analysis are 2 cm/a for the change in surface elevations and 2-3 cm/a for the horizontal flow velocities. In the upper part of the investigated area, mean flow velocities are up to 8 cm/a, whereas in the lower part, the velocities are estimated to be 1 cm/a. The morphological appearance (flow patterns) of the creeping permafrost in this area compares well with the measured velocity field (Figure 1 and Figure 5).

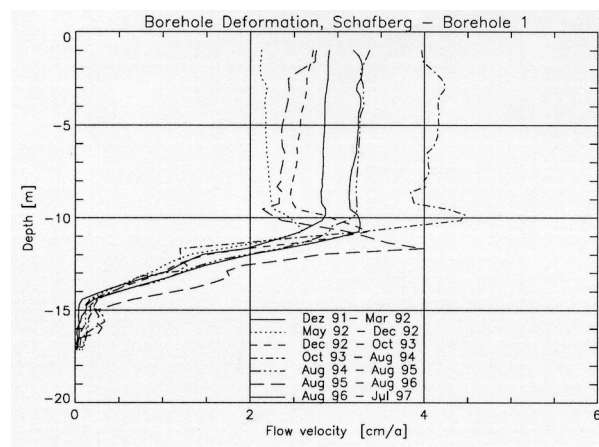


Figure 3. Flow velocity in xyz-direction at BH 1 calculated from slope and magnetic ring measurements.

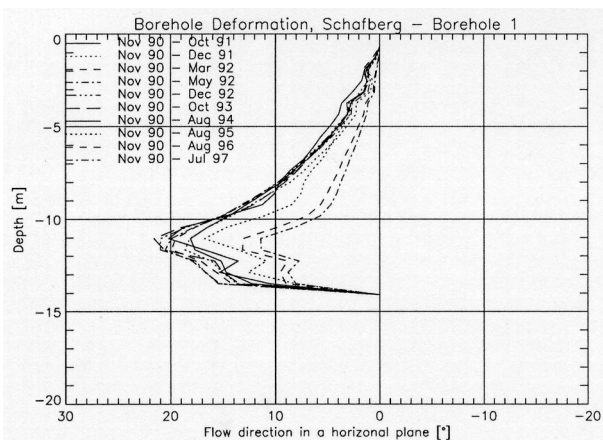


Figure 4. Flow direction as a function of depth along BH 1. The flow direction at a depth of 11 m is rotated by about 20° with respect to that at the surface.

Discussion

The photogrammetric results show a coherent velocity field, which points to stress coupling and therefore, to a continuous presence of ice-supersaturated permafrost. In addition, the borehole measurements confirm that permafrost creep occurs in ice-supersaturated layers in the ground. The flow velocities measured in the two boreholes and determined by photogrammetry are small compared to those observed on other rock glaciers in the Alps (Kääb, 1996; Wagner, 1996; Kääb et al., 1998). On the other hand, the creep velocities reported in the present study are considerably faster than creep rates published from studies in other regions such as the Arctic or the Himalayas (Bennett and French, 1991; Wang and French, 1995; Dallimore et al., 1996; French pers. comm.).

Using the findings, the influence of permafrost creep on the potential risk of natural hazards in the area of Pontresina-Schafberg can be estimated. BH 2 is situated only a few meters behind a starting zone for debris flows. This debris flow starting zone appears to be little affected by debris transport at the rock glacier front

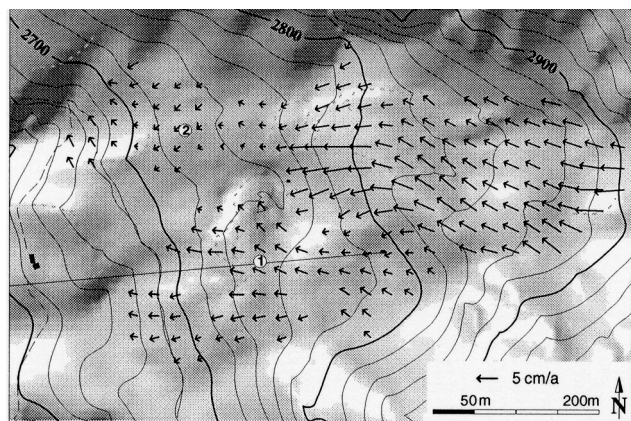


Figure 5. Mean annual surface velocities at Pontresina-Schafberg for the period of 1971-1991.

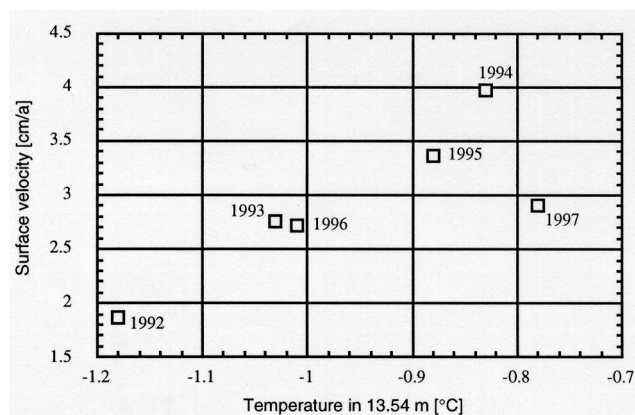


Figure 6. Annual surface velocities versus ground temperatures at a depth of about 13 m.
1 = BH 1 and 2 = BH 2.

which is moving at velocities of only up to 1 cm/a. Problems at this site of warm permafrost with temperatures close to 0°C might rather be related to possible future temperature increase. Medium-term instability and therefore increased debris flow activity cannot be excluded in a scenario of potential ground warming and permafrost degradation.

In close connection with the above-mentioned influence of permafrost temperature on natural hazards, the most remarkable finding of this study can probably be demonstrated at BH 1. In Figure 3, the observed annual flow velocities fluctuate between 2 and 4 cm/a. A comparison between the temperatures in BH 1 and these annual flow velocities show that the velocity fluctuations are probably mainly caused by variations in permafrost temperatures. In warmer years, the flow velocities are clearly higher than in colder years. Figure 6 qualitatively indicates the dependence of the annual surface velocities in BH 1 on the averaged annual temperatures (cf. Vonder Mühl et al., 1998). Due to the fact that the main deformation in the Pontresina-Schafberg boreholes occurs within depths affected by seasonal temperature variations, seasonal velocity variations

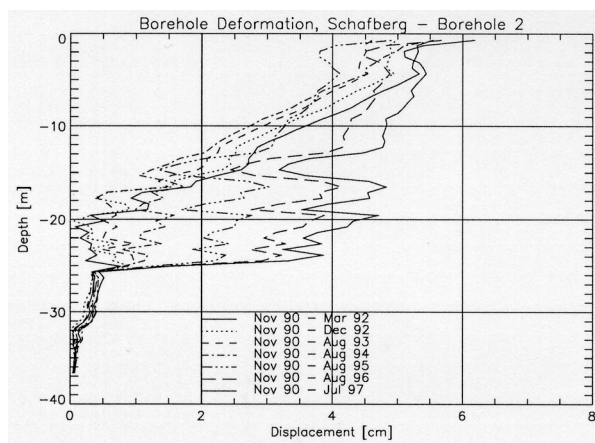


Figure 7. Displacement in xyz-direction at BH 2 calculated from slope and magnetic ring measurements.

may also exist but were not measured in these boreholes. At the nearby Murtèl rock glacier (Vonder Mühll and Haeberli, 1990; Wagner 1992), no annual variations could be detected, because the main deformation takes place at a depth of 30 m and hence, is not influenced by annual temperature variations. Therefore, BH 1 offers one of the few possibilities to study in situ the effect of 'warm' permafrost temperatures on the creep rates of ice-rock mixtures and to compare them with theoretical studies (e.g., Smith and Morland, 1982).

The general creep behaviour at BH 1 is closely linked to the stratigraphy of the borehole (Vonder Mühll and Holub, 1992). As mentioned above, the upper layer (10 m) contains about 30% ice by volume and the second layer (5 m) has an ice content of up to 80% by volume. In this second layer, 90% of the total deformation takes place at a depth between 10 and 15 m. The first layer has nearly no deformation and the second layer is deforming by undamped creep under small stress (secondary creep, Figure 2). Numerical studies of deforming permafrost by Savigny and Morgenstern (1986c) and Wagner (1992) interpret secondary creep data in terms of a simple power law after Glen (1952). Based on these studies, values for n as the exponent in the power law can be assumed to range between 1 and 3. Wagner (1996) proposes to differentiate between the weak shear zone and the other layers in rock glaciers. For all layers without the shear zone, he calculated a value of $n = 1$ and for all layers including the shear zone, a value of $n = 3$.

Vertical strain rates were calculated from the magnetic ring data in both boreholes. Total vertical deformation at the surface in BH 1 is calculated to be around -7 mm/a and at BH 2 to be around -3 to -4 mm/a. The vertical strain rates show a strongly nonlinear variation with depth along the borehole. The assumption of strain rates linearly decreasing or being constant with depth can not be confirmed by the present results (cf. Haeberli and Schmid, 1988; Käab et al., 1998).

In Figure 2, a velocity anomaly can be recognized in the ice-rich part at a depth of 10 m where velocities show an intermittent increase with depth. This anomaly can have two possible explanations. The first may be a three-dimensional effect related to the change in azimuth (rotation) of the flow vectors by about 20° with increasing depth along the borehole axis down to 11 m below the surface. The second explanation is based on the assumption of extrusion flow at this depth. Gudmundsson (1997a, b) investigated criteria for extrusion flow in glaciers by using analytical solutions for a two-dimensional flow over bedrock undulations. Applying these criteria to this particular case leads to the estimation that the wavelength of the involved bedrock undulation would have to be 30 m in order to

explain extrusion flow at 5 m above the bedrock. Unfortunately, bedrock topography along the flowline of the rock glacier through BH 1 is not precisely known. The interpretation of the observed velocity anomaly must therefore remain open. Further geophysical investigations should be carried out to better understand these effects.

BH 2 shows much less deformation than BH 1. In Figure 7, a shear zone can be recognized at a depth of 25 m, where most of the total deformation takes place. The flow velocities are lower than in BH 1 by a factor of two to three. Further observation of this borehole is needed in order to fully understand the deformation processes because rates are very small.

Conclusions and perspectives

Borehole deformation measurements combined with photogrammetric determinations of surface velocities on rock glaciers at Pontresina-Schafberg provide the following primary results:

- The investigated permafrost is relatively warm (around -1°C), several tens of meters thick and rich in ice (ca. 30 to 80% ice content by volume); it moves a few centimeters per year horizontally and several millimeters per year vertically (downwards).
- The deformation rates seem to be correlated with borehole temperatures. However, longer observations are needed to establish a quantitative relationship between deformation rates and temperatures. Therefore, measurements of deformation and temperature should be carried out at higher frequencies to determine not only annual, but also seasonal effects.
- With respect to the general natural hazard situation at this site, borehole deformations must be further observed in order to detect possible acceleration trends.
- Modelling of these creeping permafrost bodies should be possible after more years of observation and with more detailed information about the underlying bedrock. The bedrock topography should be determined with greater precision by geophysical investigations along the flowlines across the boreholes.
- In addition, better information about the geotechnical properties of the investigated permafrost is urgently needed.

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