Surface and aerial lifts with intermediate support structures founded upon glaciers

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Abstract

Alpine glaciers have been made accessible by lifts since the late sixties. Surface and aerial lifts with support structures directly founded on ice have been built. In the past years, a flexible system has been developed in cooperation with cable car companies. In this design, a holding cable fixes the heads of the intermediate supports so that the footings are free to move with the glacier flow. The footings require periodical replacement. A series of u-shaped profiles connected with longitudinal beams are used as footing. A method for a preliminary design of such foundations is outlined, which gives an admissible foundation pressure that is in agreement with that of existing foundations.

Keywords: bearing capacity, creep settlements, ice mechanics

1 Introduction

Alpine glaciers have been made accessible by lifts since the late sixties. Foundation of support structures directly upon the moving glacier ice was for the first time successfully carried out in 1968 at the Hintertux Glacier (Gefrorene Wand Kees), Tyrol. The support structures had to be replaced several times per year due to glacier movement. Since 1995, T-bar lifts have been exchanged by chair lifts. For such constructions, a higher design level was called for, e.g. a more precise survey of the glacier flow and fulfilling higher safety requirements. Likewise the standards for the foundation and replacing techniques increased. In 2003, a eight-person gondola railway with towers up to 20 m height was built on the Stubai glacier (Schaufel- and Bildstöcklferner), Tyrol. Obviously, replacing the footing of such a large and heavy tower requires much more effort than replacing the footings of a light T-bar lift tower. The construction of these large cable cars has been possible mainly due to the negative mass balance in the last twenty years, which has been accompanied by a drastic decrease in surface velocities.

2 Principal setup of the lift system

Alpine glaciers creep downhill due to the gravity, the viscosity of the ice, and the basal gliding, currently with surface velocities up to 3.5 metres per year (m/a) at the Theodul glacier, Switzerland (Suter & Funk 2002) or 4–10 m/a on the Stubai glacier in Tyrol, Austria (Lackinger 2007). The latter values result from the annual replacements of the existing lift supports between 1993 and 2001, where the higher value was at one location in 1994. These velocities are comparable to those reported by the Ice and Climate Group (2004). Glacier movement is the main challenge for the construction of such support structures. Obviously, support structures can only be placed in regions without crevasses, which has to be verified regularly.

2.1 Construction requirements

In this construction, a holding cable fixes the heads of the intermediate supports while the footings freely move with the glacier flow. For aerial lifts, the holding cable is mounted at the uphill and downhill station (figure 1).

For surface lifts, the holding cable can be anchored in ice at the downhill station. The glacier will move the downhill station and therefore increase the force in the holding cable. This force is monitored and the holding cable must be extended once the tolerable maximum force is exceeded.

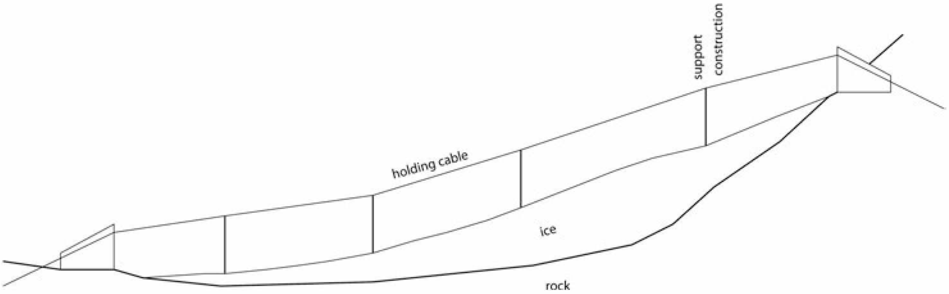

Figure 1: Schematic sketch of an aerial lift. The holding cable is fixed at the uphill and downhill station. Thus, the heads of the support structures are fixed whereas the footings can move downwards with the ice.

2.1.1 Support construction

A hinge between each footing and the support construction allows an individual shift from the glacier flow (figure 2). Several times per year, when maximum displacement is reached, the footings are moved to the original position.

The support structure can tilt along the cable axis but the hinged does not allow tilting perpendicular to the cable axis. The cable axis has to follow the flow line of

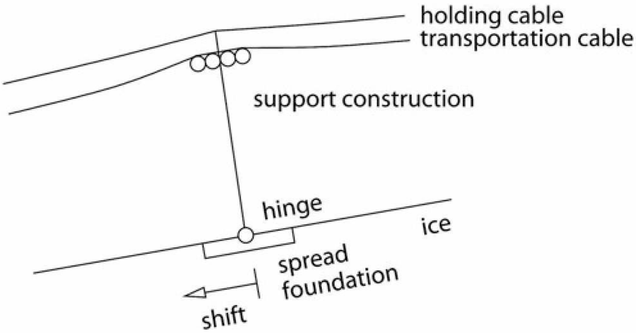

Figure 2: Schematic sketch of a support structure designed to adjust to the glacier flow.

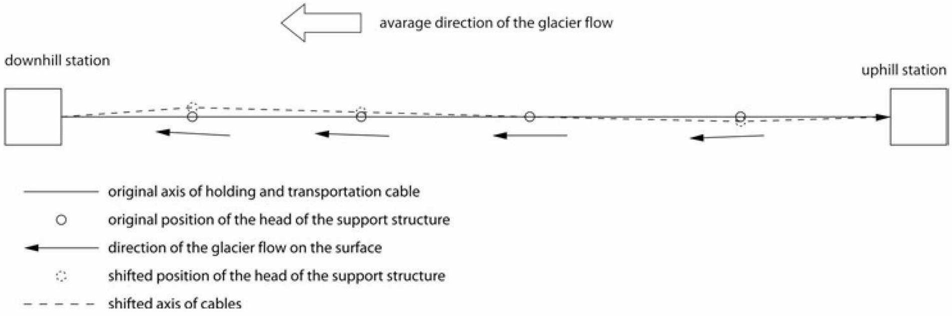

Figure 3: Original and shifted lift axis due to the glacier flow.

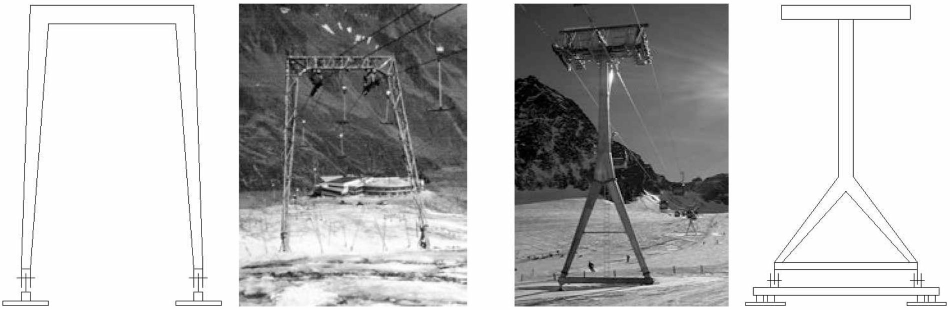

Figure 4: Possible support structures: Portal frame for surface lift (left) and Y-shaped pillar for aerial lift (right).

the glacier as accurately as possible. Inevitable local deviations of the surface flow from the average flow direction will move the support structures perpendicular to the cable axis (figure 3).

A portal frame or a pillar is usually used as support structure for a surface or an aerial lift, respectively (figure 4). Both systems have two separate spread footings to give stability against tilting perpendicular to the cable axis.

2.1.2 Footing system

A light construction system, not too deeply founded in the ice, is needed for easy and periodical replacement of the foundation. Very limited friction forces can be mobilised between foundation and ice and a minimum foundation depth is needed to sustain loads acting tangentially to the ice surface. To provide a form-locking connection with the ice, usually u-shaped profiles are installed with the side walls downwards into the ice.

Typically, spread foundations are constructed in the style of snow foundations (Mellor 1969), namely a series of u-shaped profiles perpendicular to the cable car axis connected with longitudinal beams (figure 5). The length of the u-shaped profiles and their spacing is typically large compared to the width of the profiles, thus each profile will be treated as a single strip foundation. Vertical nails could be used to enlarge the resistance against forces perpendicular to the cable car axis. However, it is better to weld transverse plates inside the u-shaped profile to ease replacement. The surface snow and firn layers have to be removed. Each profile is situated in a

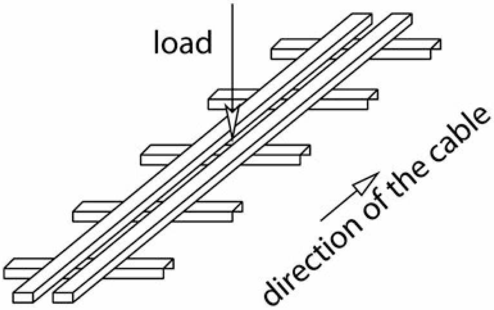

Figure 5: Schematic sketch of a typical footing system.

small trench directly in the glacier ice. Water saturated snow is packed under and around the profile to fill the trench and then freezes to almost clean ice.

2.2 Monitoring

Each footing will follow the surface flow of the glacier. As allowed by the hinge, the support structures will tilt in the cable axis. The footings will sink additionally into the ice due to the viscosity of the ice. This creep settlement can be overlaid by pressure melting and melting due to heat transport from the support structure to the foundation. Due to asymmetric loading, the creep settlement can also cause lateral tilting of the support structure. Ablation and accumulation can change the depth of the foundation. If the depth in an accumulation zone gets too deep, firn could cover and immobilise the hinge. Alternatively, the ice surface in the direct vicinity of the footing could drop below the foundation in the ablation zone (figure 6) resulting in a drastic reduction of the bearing capacity and an increase of the settlement rate.

This situation must be avoided in any case paying special attention to flowing water that can also uncover the foundation by convection melting. If necessary, the area above and around the footing must be insulated with white foil or a snow heap to reduce ablation.

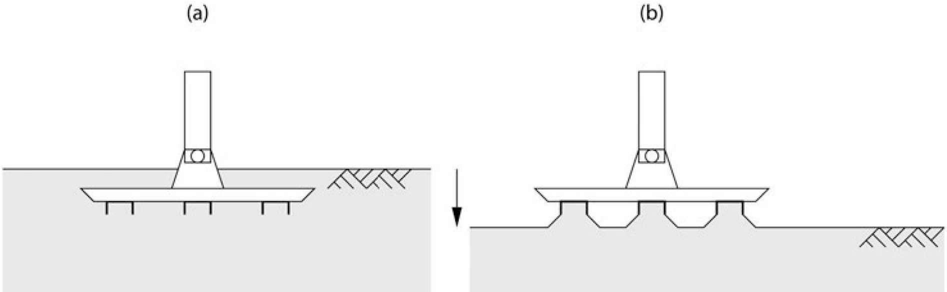

Figure 6: Originally the footing has to be covered with ice or snow (a). Ablation and/or down flow of free surface water can melt the surface cover leading to extreme situations (b) where the bearing capacity is drastically reduced.

All the above mentioned effects are hardly to predict. The construction has therefore to be insensitive to the inevitable motions and has to be under careful observation during the whole operation time. At least, regular checks should be made of:

- the depth of the foundation;
- the tilting of the tower along and perpendicular to the cable;
- the deviation of the tower head from the cable car axis.

One or several times per year, when allowable limits are reached, the footings are readjusted in the original position.

3 Design of the footing size

The series of u-shaped profiles of each footing can be treated as separate strip foundations. Thus the design approach for strip footings upon glacier ice developed by Fellin & Lackinger (2007), as outlined below, can be applied.

3.1 Ultimate limit state

The strength of ice can be described by a Coulomb relationship (Schulson 2001) with the cohesion c and the friction angle φ. The friction angle for glacier ice at the melting point (temperate ice) is very low, e.g. $\varphi \approx 0°$ (Fish & Zaretsky 1997). Such low values are neglected in the following investigation and temperate glacier ice is treated as purely cohesive material.

The bearing capacity p_u can be estimated with the slip-line field solution by Prandtl (1920), which reads for a centrally and vertically loaded strip foundation on a horizontal half space of purely cohesive material with the cohesion c:

$$p_u = (2 + \pi)\, c \tag{1}$$

Statistical evaluation of uniaxial compression tests on ice from the Stubai glacier in Tyrol (Lair 2004) and comparison with earlier published values (Michel & Toussaint 1977, Gagnon & Gammon 1995, Lawson 1999, Niehus 2002,) yields the characteristic value of the cohesion of temperate glacier ice c_k = 355 kPa and the partial safety coefficient γ_c = 1.9 (Fellin & Lackinger 2007).

The design resistance pressure p_d of a strip foundation on ice is

$$p_d = (2 + \pi)\, \frac{c_k}{\gamma_c} \tag{2}$$

for temperate glacier ice with $\varphi > 860$ kg/m.

3.2 Serviceability limit state

We can obtain an approximation of the settlement rate in the centre of a strip foundation by using the stress field of the elastic settlement problem and calculating the

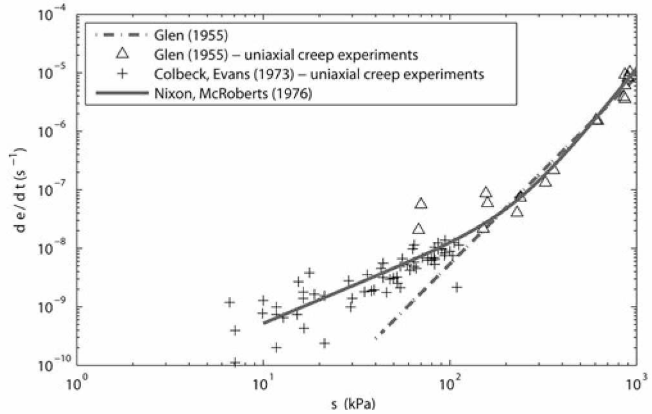

Figure 7: Uniaxial creep of polycrystalline ice at 0°C; lines denote published creep relationships; symbols mark experimental results.

vertical strain rate using a non-linear flow law for temperated glacier ice. This was conduced by Fellin & Lackinger (2007) using the flow law of Nixon & McRoberts (1976) and gives the rate of settlement $\dot{u}$ of a strip foundation with the width b loaded by the pressure p on temperated glacier ice

$$\dot{u} = \beta_1 b^{\beta_2} p^{\beta_3} \tag{3}$$

with the coefficients $\beta_1 = 8.6 \times 10^{-5}$ m kP$^{-\beta_3}$ a^{-1}b$^{-\beta_2}$, $\beta_2 = 9.2$ and $\beta_3 = 1.74$. The dimensions of the variables in this equation are: $[b]$ = m, $[p]$ = kPa and $\dot{u}$ = m/a. The flow law of Nixon & McRoberts (1976) is a better fit in the here important low pressure range than the flow law of Glen (1955) (figure 7).

However, the scatter of creep experiments is rather large (figure 7). The accuracy of the predicted settlement rate is therefore not high.

3.3 Design chart

The admissible bearing pressure of a strip foundation on temperate glacier ice is controlled by the ultimate bearing capacity and an admissible settlement rate. A design chart is provided through (3) for the serviceability limit state (figure 8). This figure shows the bearing pressures for various admissible settlement rates. All bearing pressures in this chart are well below the ultimate bearing capacity.

The designer of a foundation has to bear in mind that predicted settlement rates are rough estimates due to the uncertainty of the flow model. The construction should be insensitive to settlements.

4 Case studies

Typical foundation pressures of two cable cars built in 1998 and 2003 on the Stubai glacier are presented in table 1. Both systems have Y-shaped towers (figure 4), each

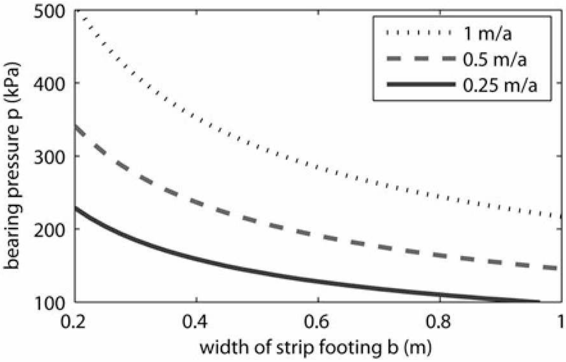

Figure 8: Bearing pressure for strip foundations on temperate glacier ice for various admissible settlement rates.

with two footings as shown schematically in figure 5. The total foundation area of each footing (2.25 m^2) is composed of five u-shaped cross beams with a length of 150 cm and a width *b* of 30 cm. The profiles' height is 10 cm with 65 cm space between the cross beams.

With the footing geometry mentioned above and the pressures resulting from the static calculation of the pylons (table 1), no problems concerning bearing capacity or settlements have arisen. The ablation on the Stubai glacier had not endangered the foundation (compare figure 6) since their construction thanks to their yearly replacements. The yearly replacing of the footings of towers, with weights up to 370 kN, did not require excessive effort.

Table 1: Cable cars on Stubai glacier: Maximal foundation pressure p_{max} *due to permanent plus variable loads, and the foundation pressure* p_G *due to own weight.*

Cable car	**year of building**	**pylon height**	p_{max}	p_G
Chair lift (6 persons)	1998	18 m	184 kPa	90 kPa
Gondola ropeway (8 persons)	2003	20 m	250 kPa	145 kPa

5 Summary

Intermediate support structures of surface and aerial lifts have successfully been founded directly on glacier ice. The main challenge in constructing such support structures is to cope with glacier movement. The main system of holding the heads of the support structures and letting the foundations follow the glacier flow requires an accurate monitoring system of the lift and a periodical replacement of the footings. The actual motions of the lift footings operating on the Stubai glacier do not inhibit their operation and maintenance. A method for preliminary design of such foundations is outlined giving an admissible foundation pressure in agreement with already safely operating cable cars.

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