

## SNOW PRESSURE ON CABLEWAY MASTS: ANALYSIS OF DAMAGES AND DESIGN APPROACH

Stefan Margreth\*

WSL Swiss Federal Institute for Snow and Avalanche Research (SLF),

**ABSTRACT:** Cableway masts are often built in slopes exposed to snow pressure. In areas with large snow depths and low ground roughness the creeping and gliding snow cover can exert huge static loads ( $>100 \text{ kN m}^{-1}$ ) on a narrow mast. Three case studies are examined where masts from cableways were completely destroyed by snow pressure forces. The snow pressure equations applied in practical use are explained and illustrated with examples. The equations are based on the snow pressure theory given in the Swiss guidelines for the design of snow supporting structures. The snow pressure depends mainly on the snow depth, snow density, slope angle, gliding factor and efficiency factor. The efficiency factor describes the ratio of the real snow pressure to that on an infinitely long plane. To prevent damage the mast can either be designed to the expected snow pressure or the gliding of the snow pack can be prevented by increasing the ground roughness by structural measures e.g. by narrowly spaced poles. Finally, we discuss possibilities for verifying and improving the presented design approach.

**Keywords:** snow pressure, snow gliding, snow cover, masts.

### 1. INTRODUCTION

The design of structures in steep snow slopes not only requires knowledge on impact forces of fast moving avalanches, but also knowledge of snow pressure forces caused by retarding the slowly moving snow cover. In areas with an abundant snow cover the static snow pressure loads can exceed the dynamic loads due to avalanche impacts. The theory of snow pressure calculation for the design of supporting structures built in long lines is relatively well established. In contrast the knowledge of snow pressure on narrow structures such as cableway masts is very limited. In Switzerland, the design of cableway masts requires consideration of the static snow pressure loads, if necessary. This provisional treatment of static snow pressure has led engineers to be overly optimistic in their selection of design loads. In winter 1999 in the Alps not only catastrophic avalanches but also high snow pressure loads were observed (SLF, 2000). As a consequence cableway masts were damaged. To improve the knowledge on snow pressure on narrow structures failure analyses of destroyed masts and back-calculation of snow

pressure loads were performed. Such failure analyses are very valuable to improve the design because full scale measurements of snow pressure forces on masts are very rare.

### 2. SNOW PRESSURE

The snow pack moves slowly and continually down slope. If these movements are braked or stopped by an object, e.g. a mast from a cableway, then the object is loaded with snow pressure. The following two types of movement of the snow pack are distinguished: snow creep and snow glide (Fig.1).

Snow creep ( $v$ ) is the resultant of vertical settlement ( $w$ ) of the snow cover and internal shear deformation parallel to the slope ( $u$ ). The cause of these motions is the weight of the snow cover that generates forces parallel and perpendicular to the slope. Typical creep rates are mm to cm per day. At the ground the snow creep is zero.

Snow glide ( $u_0$ ) is the slip of the entire snow cover over the ground without essential deformation within the snow cover. Typical glide rates are mm to more than m per day. Gliding affects snow pressure to a large extent. Therefore, snow gliding is a very important component for the calculation of snow pressure. A typical sign of fast snow glide are half-moon to sickle-shaped cracks which are the result of tensile failures. The formation of cracks is generally limited to slopes steeper than  $30^\circ$ .

---

\* Corresponding author address:

Stefan Margreth, Swiss Federal Institute for Snow and Avalanche Research (SLF), Flüelastrasse 11, CH-7260 Davos Dorf, Switzerland,  
tel: +41 81 417 0254; fax: +41 81 417 0111;  
email: margreth@slf.ch

After the formation of cracks, snow gliding increases and the highest snow pressure forces are observed. Finally, the whole snow pack can break loose on the ground to form a slip or glide avalanche. Often glide cracks are observed each winter at the same locations.

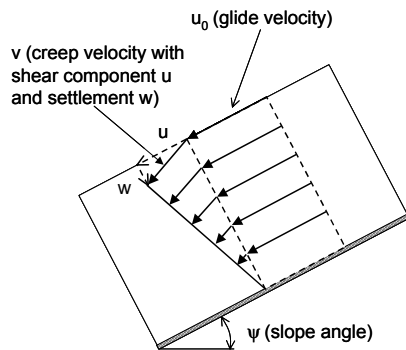


Figure 1: Schematic diagram of the creep and glide movement of the snow cover

The theory of snow glide was investigated mainly by Salm (1977) and McClung (1981). Frutiger (1967) and in der Gand and Zupančič (1966) studied the practical aspects mainly in regard to the design of defense measures against snow glide. Lackinger (1988) investigated glide avalanches in the field. Experience shows that different factors must be met before snow gliding starts. The most relevant factors are as follows:

- The roughness of the ground must be low. High glide rates occur on smooth slopes with long-bladed grass or on smooth outcropping rock surfaces with stratification planes parallel to the slope. Wet or swampy ground also facilitates glide movements.
- At the bottom of the snow cover the temperature must be above  $0^{\circ}\text{C}$  so that a thin free water layer can be formed. With a dry boundary layer (temperature below  $0^{\circ}\text{C}$ ), the snow cover does not glide even on a grass surface. Especially favourable for snow glide is if there was rainfall prior to the first snow fall, if the first snowfall in winter was abundant and early in the fall or if there were long warm periods during winter.
- Snow glide increases with increasing slope angle and starts at an inclination of  $15^{\circ}$ . If the terrain is steeper than  $25^{\circ}$  strong snow glide can start. Slopes of gentle inclination within steep terrain can retard snow glide. In the Swiss Alps snow glide occurs typically in

the pre-alps on SE to SW exposed slopes at altitudes of up to 2000 m.

- Finally a large snow depth increases snow glide because the weight increases the shear stress.

### 3. SNOW PRESSURE DAMAGE TO MASTS

#### 3.1 Case study 1: Ski lift Bärenfall, ski resort Amden, northern pre-Alps

On December 6, 1996 mast 10 of the ski lift Bärenfall was destroyed by the gliding snow cover (Fig. 2). In the evening of 3rd of December a crack with a width of 80 m was observed about 43 m above the ski lift mast (Fig. 3). The crack opened at a change of slope angle below a small cliff. Until the afternoon of 4 December the crack opened over a distance of 11 m. A maximal glide velocity of 46 cm per hour could be calculated. Consequently the ski lift mast was bent downslope by the sliding snow cover. Until the 6th of December the crack opened another 5 m, the steel-profiles broke and the mast collapsed. The distance between crack and mast was finally 26.5 m. The vertical snow depth of the displaced snow cover varied between 1.3 and 2.0 m. The slope inclination at the position of the first crack was  $35^{\circ}$  and near the mast  $30^{\circ}$ .

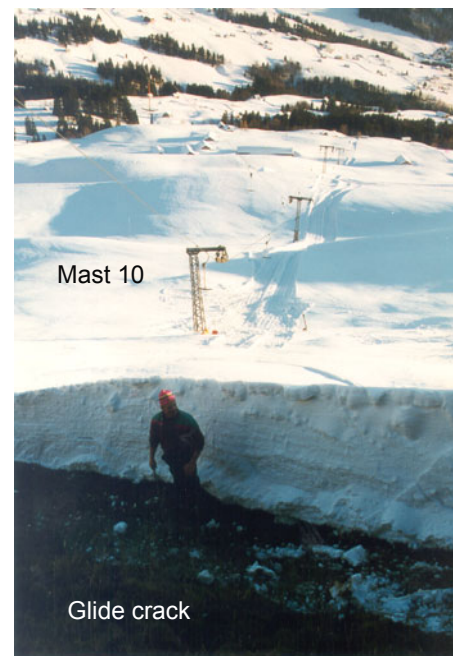


Figure 2: View from the glide crack down slope to mast 10 of the ski lift Bärenfall (case study 1).

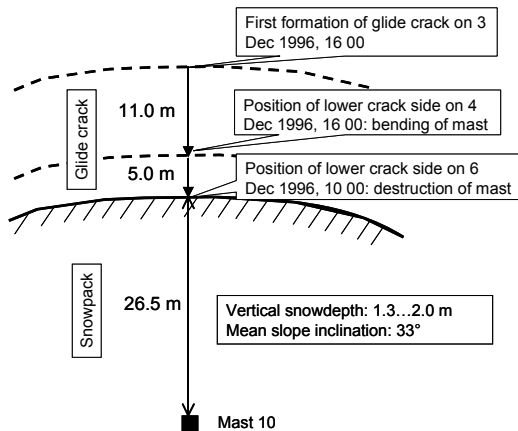


Figure 3: Situation mast 10 of the Ski lift Bärenfall with observed positions of the snow cover.

The grass surface with some indistinct cow trails was very smooth. According to measurements from near by observation stations the mean density of the snow cover was estimated to be  $300 \text{ kg m}^{-3}$ . The ski lift was built in 1984 and mast 10 was not designed to snow pressure forces. It is astonishing that the mast was destroyed so early in winter and by a snow cover with a depth of less than 2 m. The area of Amden is known as a typical snow gliding area: the elevation is 1500 m ASL, the slopes are exposed to south and the area is relatively rich in snow. October 1996 was about  $1^{\circ}$ - $2^{\circ}$  C warmer than average and clearly too wet. November 1996 was also rather warm and also wet. The permanent snow cover started relatively late, in mid November. Between November 21st and December 3rd a huge snowfall of 250 cm was recorded which resulted in snow heights far above average. Before the event a temperature increase of  $6^{\circ}$  C to  $8^{\circ}$  C was observed, but the snowpack still had negative temperatures. We assume that the relatively wet and warm fall combined with the huge snowfall at the end of November were the primary causes for the strong snow glide activity.

The lattice mast had a width of 0.8 m at its base and a height of 7.4 m. The mast was designed for vertical loads. The span of the single profiles was maximally 0.9 m. The structural analysis of the destroyed lattice mast was made with two idealized 2-D plane trusses with fixed joints. We assume that most likely the up-slope lateral angle profiles failed near their lower fixation first. The critical sections were in the angle profiles above the screw fixation of the mast to the foundation. The angle profiles with

the dimensions of 80/80/8 mm were made of steel Fe 360 with a yield point of  $360 \text{ N mm}^{-2}$ . The ultimate bending moment of the angle profile was 4.5 kNm. According to the structural analysis the mast failed with an uniformly distributed snow pressure per unit length of 72 to  $82 \text{ kN m}^{-1}$  over a height of 1.7 m. The computed failure load gives a lower boundary for the snow pressure load. We conclude that the total snow pressure acting on the mast was at least 130 to 150 kN. Mast 10 was rebuilt at the same location and protected with about 60 tripod structures to prevent the gliding of the snow cover (Fig. 10).

### 3.2 Case study 2: Chairlift Pleus, ski resort Elm, northern Alps

On 23 February 1999 the gliding snow cover displaced mast number 7 of the chairlift Pleus over a distance of approximately 8 m down slope. The concrete foundation of the mast was pressed through the ground like a plough (Fig. 4).



Figure 4: Destroyed foundation of mast 7 of the chairlift Pleus. The shallow foundation was displaced over more than 8 m (case study 2).

The shallow foundation was not anchored to the ground. The main reason for the failure was that the snow pressure force was bigger than the shear resistance of the foundation. The ski resort was closed at the time. After snow melting it could be observed that the gliding snow cover destroyed the vegetation layer at several locations. Also rocks up to a diameter of 2 m were displaced over several meters by the gliding snow cover. The area is known for strong snow gliding. The chairlift was built in 1982. Mast 7 was designed for an avalanche pressure of  $12 \text{ kN m}^{-2}$  over a height of 4 m. The mast foundation consisted of a concrete wedge with a height of 5.2 m and a mean width of 3.2 m (Fig.

5). The depth of the foundation into the ground varied between 1.2 m and 2.3 m. The mean slope angle is  $28^\circ$ . The slope exposition is Southwest. The SLF was charged to analyse the damage and to determine the snow pressure for a re-construction of the mast.

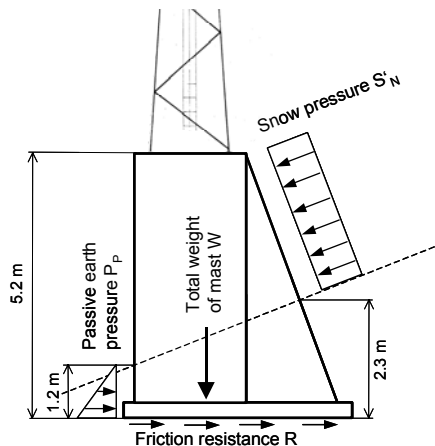


Figure 5: Cross-section of the foundation of mast 7 of the chairlift with resisting and driving forces.

In February 1999 there were abundant amounts of snow in the area of Elm. At the location of the mast at 1900 m ASL the snow height was about 4 m, which corresponds to a return period of 50 years. The snow density was about  $320 \text{ kg m}^{-3}$ . After February 21st an increased snow gliding period was observed. In Elm the temperatures in mid February were low: on 13 February  $-19^\circ \text{ C}$  were measured. Afterwards, the air temperature increased to  $0^\circ \text{ C}$  on 21 February and dropped down again to  $-12^\circ \text{ C}$  on 23 February. We assume that the big snow heights in combination with the temperature increase caused the strong snow gliding in the area of Elm.

The snow pressure on the mast could be back calculated from the resistance of the foundation (Fig. 5). The foundation slides if the resisting forces (friction between base and soil, passive earth pressure) are smaller than the driving force (snow pressure). The friction force depends on the total weight of the mast (dead loads and live loads) multiplied with the tangent of the friction angle. With a total weight of 674 kN, a friction angle of  $21^\circ$  and a passive earth pressure of 87 kN the total snow pressure on the mast was at least 472 kN. With a snow thickness of 3.5 m (perpendicular to the ground surface) the resulting snow pressure per unit length was  $135 \text{ kN m}^{-1}$ . Mast 7 was reconstructed

considering the back calculated snow pressure load.

### 3.3 Case study 3: Chairlift Käserstatt-Hochsträss, ski resort Hasliberg, Bernese Oberland

On 14 March 1999 the lateral loading due to the gliding snow cover on mast number 2 of the chairlift Käserstatt-Hochsträss increased continuously. On the previous day the snow cover was removed around the mast on a distance of approximately 2 m. In the morning the snow pressure equalled the resistance of the mast. The mast was bent continuously downslope. At 11.45 a.m. the wire rope jumped out of the cable roll and was held at the very end of the safety cable holder. Consequently the fully occupied chairlift stopped. In a dramatic rescue operation 200 persons were evacuated from the chairs by helicopter. Shortly after the rescue was completed, mast 2 collapsed (Fig. 6).

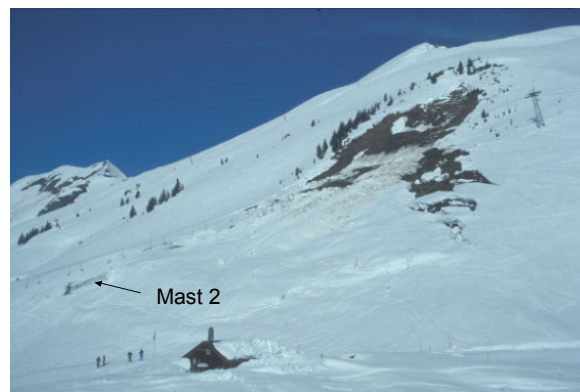


Figure 6: Overview chairlift Käserstatt-Hochsträss with destroyed mast 2 (16.3.1999). Enlargement of glide cracks and formation of folds in the pressure zone below mast 2.

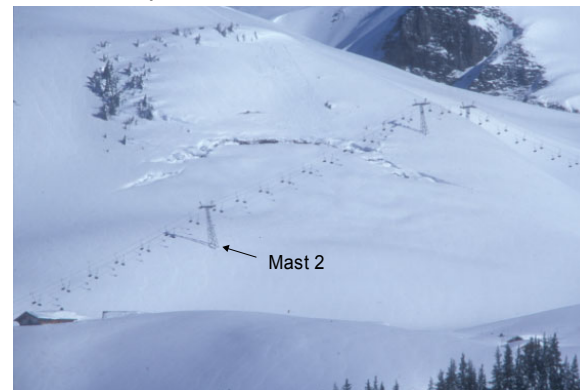


Figure 7: Chairlift Käserstatt-Hochsträss on 26.2.1999. First glide cracks have opened.

The SLF was charged to investigate the accident. The investigation showed that the

destruction was caused by the slow gliding of a 20 m long snow-slab. Above this snow-plate a 40 m wide crack with a width of 3 to 5 m had opened. The ground surface was wet and very slippery. The mean inclination between the crack and the mast was 25°. The ground temperature was +0.2° C and the snow temperature varied between 0° C and -1° C. The mean snow density was 390 kg m<sup>-3</sup>. The snow pack was very hard (hand test: pencil to knife blade) and near the bottom a horizontal ice layer of several cm was observed. The snow pack acted on the mast more like a stiff slab than a viscous fluid. A first glide crack with a width of approximately 120 m was observed on 26 February around 70 m above the mast (Fig. 7). Until 14 March several new glide cracks formed and the total glide distance was between 10 m and 35 m (Fig. 8 and 9). The mean glide velocity was estimated to be between 0.6 and 2.0 m per day. One of the reasons for the high snow gliding activity at Hasliberg was the huge snow depth of 3.5 m in February 1999, which corresponds to a return period of 10 to 20 years. At the location of the mast a snow thickness of 2.7 m was measured. The increased glide rate around the 14 March might originate from the air temperature increase of 15° C from -8° C to +7° C in the week before. In the morning of 14 March the air temperature was +3° C.

The chairlift Käserstatt-Hochsträss was built in 1967. Mast 2 was designed for vertical loads. Horizontal snow pressure loads were not considered in the design. The lattice mast, made of steel Fe 360 with a yield point of 360 N mm<sup>-2</sup>, had a width of 2.5 m at the base and a height of 14.2 m. The span of the single profiles was at most 2.4 m. The most likely failure scenario was due to local failure of the up-slope lateral profiles. The critical sections of the angle profiles were in the middle of their span. For the computation of the ultimate failure load a simplified structural model of the 3-D lattice mast was idealized consisting of two 2-D plane trusses with fixed joints. The ultimate bending moment of the angle profiles with the dimensions of 100/100/8 mm is 7.2 kNm. According to the back calculations the angle profiles failed with a evenly distributed lateral snow pressure per unit length of minimally 60 kN m<sup>-1</sup>. The ultimate bending moment gives a lower boundary for the snow pressure load. We assume that after the local destruction of the profiles the global stability of the mast became critical. For a global destruction of the up-slope

angle profiles at their lower fixation the horizontal snow pressure had to be larger than 90 kN m<sup>-1</sup>. The total snow pressure on the mast was at least 160 kN. In summer 1999 the chairlift was replaced and mast 2 was moved up-ward out of the main hazard area. For the design we proposed to apply a snow pressure of 70 kN m<sup>-1</sup> over a height of 3.0 m which corresponds to a return period of 50 years.

#### 4. SNOW PRESSURE MODEL ACCORDING TO THE SWISS GUIDELINES

The theory of snow pressure calculations was mainly developed in regard to the design of snow supporting structures in the starting zone of avalanches. According to Salm (1977) the first attempts to calculate snow forces on supporting structures were made by considering a snow block lying between two barriers and with dry friction resistance on the ground. This model was considered to be unrealistic because of linear increase of snow pressure with the slope distance between the two structures. Haefeli (Bader et al. 1939) introduced in his one-dimensional snow pressure calculations the concept of a "back-pressure zone" behind the barrier. The back-pressure zone is the range behind the barrier where additional compressive stresses are created. On the base of Haefeli's formulations the resultant snow pressure  $S'_N$  per unit length across the slope on a rigid wall was formulated in the Swiss Guidelines (1990) as follows:

$$S'_N = \rho \cdot g \cdot \frac{H^2}{2} \cdot K \cdot N \quad (\text{kN m}^{-1}) \quad (1)$$

In Equation (1),  $\rho$  is the average snow density (to m<sup>-3</sup>),  $g$  is the acceleration due to gravity (m s<sup>-2</sup>) and  $H$  is the vertical snow depth (m). The equation assumes a triangular shaped creep profile and accounts for snow gliding using the gliding factor  $N$  (see Fig. 1). In the Swiss Guidelines  $N$  was empirically classified according to field-tests with respect to ground roughness and slope exposition (see Table 1).  $K$  is the creep-factor which depends on the snow density  $\rho$  (to m<sup>-3</sup>) and the slope angle  $\psi$  (°). According to the Swiss Guidelines the creep-factor  $K$  can be approximately computed as follows:

$$K = (2.50 \cdot \rho^3 - 1.86 \cdot \rho^2 + 1.06 \cdot \rho + 0.54) \cdot \sin 2\psi \quad (2)$$

Table 1: Gliding factor N in relation of the ground classification according to the Swiss Guidelines (1990)

Ground classification		Gliding factor N		Gliding intensity:
		Slope exposition: WNW-N-E	Slope exposition: ENE-S-WNW	
I	- Big boulders, rocks >30 cm	1.2	1.3	Small
II	- Large bushes > 1 m, bumps, mounds > 50 cm - Scree 10-30 cm	1.6	1.8	Medium
III	- Short grass - Bushes <1 m - Fine rubble alternating with grass and small shrubs - Grass with indistinct cow trails	2.0	2.4	Strong
IV	- Smooth long-bladed grass - Smooth rock plates with stratification planes parallel to the slope - Swampy depressions	2.6	3.2	Extreme

Equation (1) is valid for infinitely long planes. On small obstacles such as masts additional end-effect forces appear. The influence width of a small obstacle is much bigger compared to the width of the object itself mainly because of the three-dimensional viscous flow of the snow pack around the object. Haefeli (1951) introduced the efficiency factor  $\eta_F$  of a structure with regard to snow pressure, i.e. the ratio of the real force to that of an infinitely long plane, acting over the same length. The efficiency  $\eta_F$  was defined in relation to the snow thickness  $D$  in (m) and the width of the structure  $W$  in (m). According to practical experience for high snow gliding and for small snow thicknesses this approach gives too small values. Therefore, the equation was modified with an additional factor  $c$  to account for the intensity of snow gliding and the snow depth:

$$\eta_F = 1 + c \cdot \frac{D}{W} \quad (3)$$

The factor  $c$  ranges from 0.6 for locations with a very small snow gliding to 6 for locations with extreme snow gliding. In Table 2 the  $c$  factors are proposed according to practical experiences in relation of the snow gliding

intensity. The  $c$  factor has to be determined by a careful analysis of the topographical and ground conditions. Furthermore, engineers are not interested in the force per running length, but in the load distribution over the height. Based on equations (1) and (3) the average snow pressure  $S'_{N,M}$  per unit length on a narrow obstacle as a mast can be expressed by:

$$S'_{N,M} = \rho \cdot g \cdot \frac{H^2}{2} \cdot K \cdot N \cdot \eta_F \cdot \frac{W}{D} \quad (\text{kNm}^{-1}) \quad (4)$$

To get the total snow pressure  $S_{N,M}$ ,  $S'_{N,M}$  has to be multiplied by the snow thickness  $D$ . Equation (4) is used in Swiss practice for the design of small obstacles as masts of cableways or poles to snow pressure forces. Normally only the snow pressure parallel to slope is considered and the force component perpendicular to the slope is neglected. The snow pressure is assumed to be uniformly distributed (Fig. 8) over the snow thickness.

Larsen (1998) performed measurements of snow pressure on masts in Norway during several years and developed a snow pressure model. The Larsen model was developed for situations without snow gliding. It gives very similar results to the Swiss Guidelines-model if snow gliding is non-existent or small.

Tab. 2: The  $c$ -factor for the calculation of the efficiency  $\eta_F$  in relation of the snow gliding intensity and the slope exposition

Gliding intensity and situation	Ground classification		c factor:
	Slope exposition: WNW-N-E	Slope exposition: ENE-S-WNW	
Small	Class I-III	-	0.6
Medium	Class IV	Class I-II	1.0
Strong	-	Class III	1.5
Extreme and big snow depth (>2-3 m).	-	Class IV	2.0
Extreme and small snow depth (<2-3 m).	-	Class IV	6.0

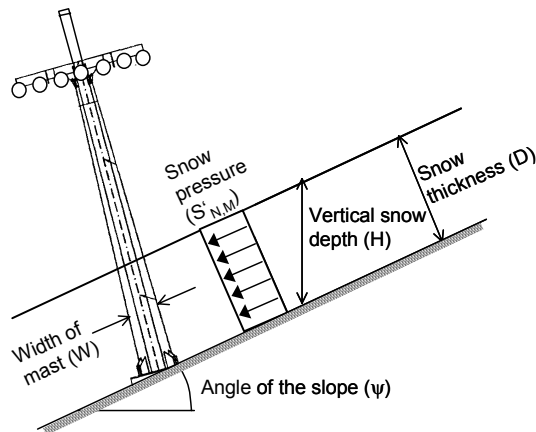


Figure 8: Schematic drawing of snow pressure acting on a mast.

## 5. APPLICATION OF THE SNOW PRESSURE MODELS

We applied the snow pressure model according to the Swiss Guidelines (1990) for the three destroyed masts, which were presented in the case studies. The input values were taken from field measurements or from estimations. The gliding factor  $N$  was assessed according to Table 1 and the factor  $c$  according to Table 2. The results are summarized in Table 3. At the locations of Pleus (case study 2) and Käserstatt (case study 3) with a gliding factor  $N$  of 3.2 and a  $c$ -factor of 1.5 the back calculated snow pressure forces are reproduced rather well. For the location Bärenfall (case study 1), where the

snow thickness was only 1.7 m, a gliding factor  $N$  of 3.2 and a shape factor  $c$  of 6 must be applied for a satisfying computation of the snow pressure. With a mast diameter of 0.8 m the corresponding influence width is 10.9 m. At this location the back calculated snow pressure is with 72 to 82  $\text{kN m}^{-1}$  very large for a snow thickness of only 1.7 m.

In Figure 9 the snow pressure on a mast with a diameter of 1.0 m on a slope with an inclination of  $30^\circ$  was calculated in relation of the snow depth. The calculations with the model according to the Swiss Guidelines were made with four different snow gliding factors and corresponding  $c$  factors. In Figure 9 the snow pressure calculated with the Larsen-model and the back calculated failure loads of the three case studies are also given. The Larsen model should not be applied in situations where snow gliding is expected. The Swiss Guidelines-model reproduce the back calculated snow pressure forces in the three case studies rather well. The correct assessment of the snow gliding factor and the snow depth, however, is crucial for a reliable calculation of the snow pressure.

## 6. MEASURES AGAINST SNOW GLIDING

Wherever possible masts should be positioned out of the main snow gliding areas. Steep slopes, areas with small ground roughness and depressions should be avoided. Positions on ridges or terrain terraces are favourable. Masts which are exposed to snow pressure forces can be reinforced. In Swiss practice masts of cableways are designed to snow pressure for a snow depth with a return

Tab. 3: Snow pressure calculation with the Swiss Guidelines model for the 3 investigated case studies

				Case study 1 Ski lift Bärenfall	Case study 2 Chairlift Pleus	Case study 3 Chairlift Käserstatt
Case studies	Back-calculated failure load	$S'^*_{N,M}$	( $\text{kN m}^{-1}$ )	72-82	135	60-90
	Back-calculated total failure load	$S^*_{N,M}$	( $\text{kN}$ )	130-150	472	160-243
Swiss Guidelines model Eq. (4)	Vertical snow depth	$H$	(m)	2.0	4	3.0
	Snow thickness	$D$	(m)	1.7	3.5	2.7
	Slope angle	$\psi$	( $^\circ$ )	33	28	24
	Snow density	$\rho$	( $\text{kg m}^{-3}$ )	300	320	390
	Creep factor	$k$	(-)	0.69	0.64	0.61
	Gliding factor	$N$	(-)	3.2	3.2	3.2
	$c$ -factor	$c$	(-)	6	1.5	1.5
	Efficiency factor	$\eta_F$	(-)	13.6	2.7	2.8
	Width of mast	$W$	(m)	0.8	3.2	2.3
	Snow pressure per unit length	$S'_{N,M}$	( $\text{kN m}^{-1}$ )	71	124	77
	Total snow pressure	$S_{N,M}$	( $\text{kN}$ )	128	438	208

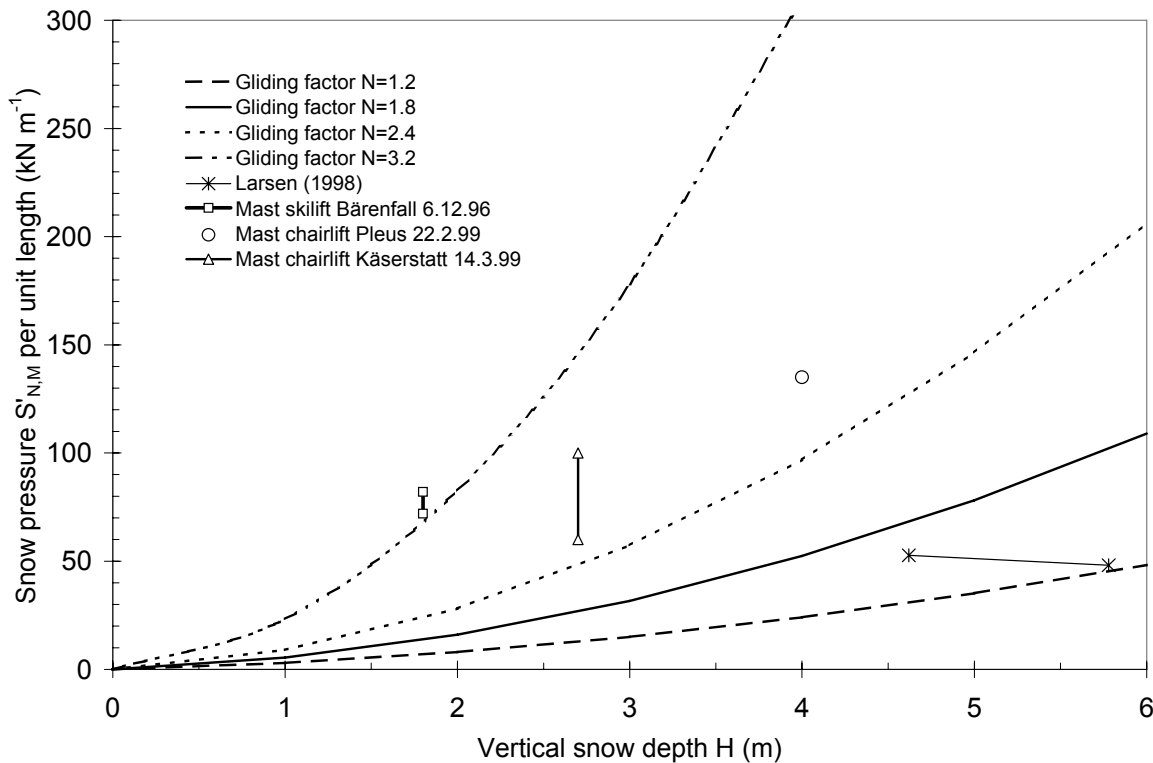


Figure 9: Calculation of snow pressure on a mast with a diameter of 1 m on a 30° slope in relation of the gliding factor N. Additionally the back calculated snow pressure of the case studies and according to the equation of Larsen are shown.

period of 30 years. For the structural design of the mast a load coefficient of 1.5 and an uncertainty coefficient of 1.1 are applied.

Snow glide can also be prevented by structural measures. The main goal of these measures is to increase the ground roughness. The following methods are common (Leuenberger, 2003):

**Tripod structures:** Tripod structures made of wood prevent the snow pack from gliding and also creeping (Figure 10). Typical structure heights are 150 cm and structure width is 200 cm. The structures are anchored to the ground with wire ropes or steel pilings. Tripod structures are best arranged in a triangular grid where the intermediate distance varies between 150 cm and 250 cm. For the protection of one hectare approximately 1'000 tripod structures are necessary.

**Pilings:** The snow pack is anchored to the ground with wooden piles. A narrow spacing of the single piles is more important than a large pile height. The minimum pile height above the ground is 30 – 50 cm. According to experience

the ratio of depth of burial to the piling height above ground has to be equal to 2:1. For a circular cross section a diameter of 10 cm is appropriate. The slope parallel distance between the piles depends on the slope inclination. For a 30° slope the slope parallel distance is 200 cm whereas an arrangement in a triangular grid is preferred.



Figure 10: Tripod structures for the protection of the repaired mast 10 of the Bärenfall ski lift (case study 1).



Temporary measures: If a location is easy accessible the snow pack can be removed around the mast by snow grooming vehicles. The snow is best removed continuously during winter so that a thick snow cover can not accumulate. A removal by hand is hardly possible if strong snow gliding has started. Sometimes it was attempted to control the gliding snowpack with explosives. However, there is only success if the snowpack is removed in fragments with a narrow grid of blast holes, similar to rock blasting. Another possibility might be to decrease the stability of the gliding snowpack by introducing water into a glide crack. However there is only little information available on the application of this method (Jones 2004).

## 7. CONCLUSIONS

In this paper, a simple model for the calculation of snow pressure forces on narrow obstacles as masts for cableways has been demonstrated and applied to three case studies, where masts were destroyed because of snow pressure. The model is based on the Swiss Guidelines (1990). In comparison to an infinitely long obstacle, end-effect forces also have to be considered. The corresponding influence zone can be much wider than the diameter of the mast. This effect is taken into consideration by introducing an efficiency factor whose value is determined according to practical experience. In the case studies the efficiency factor varied between 2.7 and 13.6. For small snow depths and extreme snow gliding the efficiency factor increases significantly. Beside the snow depth, the intensity of snow gliding also influences the snow pressure. The largest uncertainties consist in the assessment of the snow gliding and efficiency factor. The snow pressure model according to Larsen gives a lower boundary for snow pressure and should be only used in situations where snow gliding can be excluded.

Finally, we propose to establish a test site where snow pressure forces on masts can be measured directly. For areas with snow gliding direct measurements do not exist. Such a test site should include instrumented masts with different diameters, several glide shoes, temperature gauges in the ground, snow cover and air and a snow depth gauge. Further the snow pack should be monitored regularly. With such field measurements the presented snow pressure model could be improved.

The design of structures in snow slopes, however will always require an estimation of the glide capability of the snowpack, as well as the snow depth. The determination of these quantities will always demand experience and observations. It is recommended to study an area in detail before a mast is constructed.

## REFERENCES

- Bader, H. et al. 1939. Der Schnee und seine Metamorphose, von H.Bader, R.Haefeli, E.Bucher, J.Neher, O.Eckel, C.Thams, P.Niggli. Beiträge zur Geologie der Schweiz. Geotechnische Serie. Hydrologie, Lief. 3.
- Frutiger, H. and J. Kuster. 1967. Über das Gleiten und Kriechen der Schneedecke in Lawinenverbauungen, Schweiz. Zeitschrift für Forstwesen, Nr.10, 633-643.
- Gand, H.R. in der and M. Zupančič. 1966. Snow gliding and avalanches. International Association of Scientific Hydrology Publication 69 (Symposium at Davos, 1965), 230-242.
- Haefeli, R. 1951. Neuere Entwicklungstendenzen und Probleme des Lawinenverbaus im Anbruchgebiet. Mitteilungen des Eidg. Institutes für Schnee- und Lawinenforschung, Nr.9, 28-56.
- Jones, A. 2004. Review of Glide Processes and Glide Avalanche Release. Canadian avalanche association Volume 69, 53-60.
- Lackinger, B. 1988. The problem of the glide avalanche. Proc. Interpraevent 1988, Graz, 205.226.
- Larsen, J.O. 1998. Snow-creep forces on masts. Ann. Glaciol., 26, 19-21.
- Leuenberger, F. 2003. Bauanleitung Gleitschneeschutz und temporärer Stützverbau. Davos, Eidg. Institut für Schnee- und Lawinenforschung. 97p.
- Salm, B. 1977. Snow forces, J.Glaciol., 19, 67-100.
- McClung, D.M. 1981. A physical theory of snow gliding. Can. Geotech. J., 19, 401-412.
- SLF. 2000. Der Lawinenwinter 1999. Ereignisanalyse. Eidg. Institut für Schnee- und Lawinenforschung Davos, 588p.
- Swiss Guidelines. 1990. Richtlinien für den Lawinenverbau im Anbruchgebiet. Bern, Eidg. Forstdirektion und Eidg. Institut für Schnee- und Lawinenforschung.