NEW TECHNICAL GUIDELINE ON SNOW SUPPORTING STRUCTURES IN AVALANCHE STARTING ZONES

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ABSTRACT: The purpose of snow supporting structures is to stabilize the snow pack so that the release of avalanches is prevented. The structures, which have been successfully used for more than 60 years, belong to the most important structural avalanche defense measures. More than 1000 km of such structures are in service in the European Alps. We present the newest edition of the guidelines that were published in 2007. The guideline regulates the planning and the design of snow supporting structures. An overview of the effects of snow pressure and instructions on the planning of defense structures in permafrost is given. Further, the procedures and criteria for type approval, together with the requirements for supporting structures and anchor grout are specified. The guideline draws heavily on past experience gained with supporting structures, and is complementary to the relevant engineering codes. It is directed towards designers and project engineers. In the newest edition the experiences of the avalanche winter 1999 are included and furthermore new insights on the maintenance and design of the structures and their foundations. The guidelines that are applied all over the world allow the correct application of supporting structures to ensure a long service life.

KEYWORDS: Avalanche protection, snow supporting structure, snow pressure

1. INTRODUCTION

Alongside protective forests, snow supporting structures represent the primary form of protection from avalanches in Switzerland and the neighbouring alpine countries. The first supporting structures, consisting of a supporting plane and supports made of steel, were built in the 1940s. They replaced terrace walls that had a poor effectiveness and were relatively expensive. The catastrophic avalanche winter of 1950/51 resulted in many new defence projects and in a complete change to modern snow supporting structures, consisting of prefabricated elements. The construction materials were steel, concrete and aluminium. Today the use of steel dominates (Fig. 1). In the first years most of the structures were designed too weakly – damages occurred frequently. That is why in 1955 first provisional guidelines on the design of snow supporting structures were elaborated, which were definitively published in 1961 (SLF, 1961). B. Salm from the Swiss Federal Institute for Snow and Avalanche Research SLF mainly elaborated the guidelines in collaboration with Prof. R. Haefeli and experts from the cantons. The guidelines were revised in 1968 (SLF, 1968) and 1990 (BUWAL and WSL, 1990), when the new foundation technology with anchors and micropiles was introduced.

Fig. 1: Snow supporting structure with 2 supports and a structure height Dk of 4.5 m (Matthorn, Alpnach, Switzerland).

The updated version of the guideline (Margreth, 2007), which is presented in this paper, is the product of over 50 years' development. The previous edition of 1990 was extended to include the latest engineering design codes, the layout has been revised, experiences from the avalanche winter 1999 included, and the chapters on type

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approval test, avalanche defense in permafrost and the use of anchor grout in supporting structures added. The guideline is available in German, French, Italian and English. The revision was made in close collaboration with the Federal Office for the Environment (FOEN), the Federal laboratories for Material Testing and Research (EMPA) and specialist form the Expert Commission for Avalanches and Rockfall (EKLS). The guideline specifies the requirements when applying for federal subsidies for avalanche supporting structures in Switzerland. It is applied in different countries:

- In Austria the guideline is applied for the design of the structures whereas the distance between the structures is calculated in a different way. At present the Austrian Standard Institute elaborates an ON-Rule on snow supporting structures on the base of the guideline.
- In France the guideline was partly considered by the French standards association (AFNOR) for the elaboration of guidelines on snow bridges, snow rakes and snow nets (AFNOR, 1992), which are currently in revision.
- In Italy and Germany the guideline is also applied.
- In Iceland the guideline is applied with relatively small modifications taking into account the higher snow densities and the lower snow gliding (Johannesson and Margreth, 1999).

2. OVERVIEW

The guideline (Margreth, 2007) applies to the planning of supporting structures in the avalanche starting zone which are situated at high altitudes on highly inaccessible slopes having a variety of different ground characteristics. Simple, inexpensive, robust and well-proven structural methods are therefore essential for successful and durable implementation of avalanche defense structures. The guideline draws heavily on the experience obtained in the past with supporting structures. The information contained in the presented guideline is based on heavy simplifications of the true situation. Users should be aware that this requires a high level of competency on their part. The content of the guideline is specified in Fig. 2. The guideline is aimed at designers and project engineers. Section 5 "Dimensioning of separated supporting structures" and Section 8 "Type approval tests" are addressed particularly to designers. Section 3 "Planning of snow supporting structures" and in relevant situations, Section 7 "Avalanche defense structures in permafrost", must be observed by project engineers.

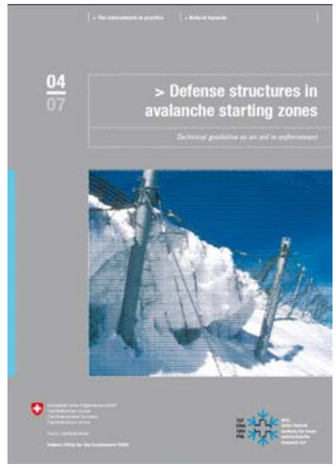

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Fig. 2: Cover and contents of the technical guideline "Defense structures in avalanche starting zones" (Margreth, 2007).

3. PLANNING OF SUPPORTING STRUCTURES

The purpose of supporting structures is to prevent avalanches being triggered, or at least to prevent snow movements occurring that could lead to damage. Snow movements cannot be completely prevented. Supporting structures cannot stop fully developed avalanches.

Snow supporting structures are designed to withstand the creeping and gliding snowpack. The structures are anchored in the ground approximately normal to the slope and extend up to the surface of the snowcover. Thus a restraining effect occurs, so that the stability of the snow pack is increased in the so-called back-pressure zone. When fractures occur, the supporting structure prevents the old snow pack being dragged downwards, and limits the area and the mass of the avalanche by their retention (Fig. 3). Avalanches between the structures are mostly released either after very loose or heavy new snowfalls or during springtime situations. Soft and wet slabs seem to be more problematic than hard slabs.

The most common structure types are rigid snow bridges with horizontal steel crossbeams (Fig. 1) and flexible snow nets with a supporting surface made of a wire rope nets (Fig. 8). Snow nets are less sensitive to creep movement and rockfall, but more difficult to anchor in loose ground. Supporting structures are generally required for slope inclinations between 30° and 50°. The highest fracture lines of an avalanche should lie in the back-pressure zone of the top most structure. The revised guidelines emphasise that a check should be made whether avalanches could be triggered in secondary starting zones further above, which could impinge on the structures. The supporting structures should extend downslope until either the slope inclination definitely drops below 30° or it may be assumed that avalanches breaking off further below will be too small to be dangerous. Laterally the area with supporting structures should extend to natural terrain borders such as terrain ridges. If this is impossible the end of the structure-lines should be arranged by tapering back in the downward direction.

Fig. 3: Avalanche release next to snow supporting structures. The structures are arranged in continuous lines (Nolla, Oberwald, Switzerland. 12 February 1999).

The continuous arrangement of structures is preferred (Fig. 3). The length of the lines extends between 20 and 50 m. The advantage is that the propagation of shear fractures is largely hindered beyond the lines both in the upward and downward directions and the loading of the structures by end-effect loads occurs only at the end of the lines. At the end of a line stronger structures are normally necessary, for example with double girders and supports. In exceptional cases e.g. in a narrow gully or very uneven terrain separated single structures may also be applied.

The height of the structure H_k must be at least as great as the extreme snow height anticipated at the site of the supporting structure. According to the guidelines the return period of the extreme snow height should be 100 years. This is the fundamental condition to be fulfilled to provide protection from avalanches during catastrophic avalanche cycles as for example in February 1999 in the Swiss Alps (Margreth et al. 2000), and dictates the procedures for dimensioning the defense structures. In order to have any chance of fulfilling this requirement, one must have a detailed knowledge of the snow depth distribution in the starting zone. Snow depth measurements with stakes should be carried out during several winters and the results should be compared with long-term snow data taken at nearby observation stations. Typical heights of the grate D_k vary between 3.0 m and 4.0 m corresponding to a snow height H of 4.2 m and 5.7 m on a 45° slope.

The calculation of the distance between structures in the line of slope was not modified in the new edition. The distance is so designed that the structures suffer no damage neither from snow pressure nor form dynamic avalanche loads. The distance is calculated on the base of the structure height H_k, the angle of friction between the ground and the snow ϕ and the glide factor N. The distance measured in the line of slope varies e.g. for a effective height of the grate D_k of 3.5 m for a slope inclination of 31° between 36 m and 43 m and for a slope inclination of 45° between 20 m and 25 m. Experience has shown that in regions with heavy precipitation, distances shorter than those proposed in the guidelines may have to be chosen.

When planning supporting structures the assessment of site factors such as the glide factor or altitude factor are important. The empirical glide factor N, which expresses the increase in snow pressure for movement of the snow cover along the ground, depends on the ground roughness and the slope exposition (solar exposure). It is classified into 4 ground classes and 2 exposure sectors varying between 1.2 and 3.2. The guideline stresses also the importance of the investigation of the foundation conditions such as for example the determination of the ground resistance by means of anchor pull-out tests.

4. OVERVIEW OF SNOW PRESSURE EFFECTS

The snow pressure formulae applied in the guideline base on Haefeli (Bader et al., 1939) who introduced in his one-dimensional snow pressure calculations the concept of a “back pressure zone” behind the barrier. On the base of Haefeli’s formulations the resultant snow pressure S'_N per unit length across the slope on a rigid wall is formulated in the guideline (Margreth 2007) as follows:

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

In Equation (1), ρ is the average snow density (to m^{-3}), g is the acceleration due to gravity ($m\ s^{-2}$) 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. K is the creep-factor which depends on the snow density ρ ($t\ m^{-3}$) and the slope angle ψ (°). For a snow density ρ of 0.3 $t\ m^{-3}$ and a slope inclination ψ of 45° K is 0.76. The snow pressure component normal to the slope S'_Q on a rigid supporting surface normal to the slope (Fig. 4) occurs when the settling movement of the snow at the surface is prevented by adhesion and surface roughness. It has the value:

$$S'_Q = S'_N \frac{a}{N \cdot \tan\psi} \quad (kN\,m^{-1}) \qquad (2)$$

where a is a constant which can vary within 0.2 to 0.5, the lower value associated with dense and the higher with loose snow. When the supporting surface is not normal to the slope, the components S'_N and S'_Q must be incremented by the weight G' of the snow prism formed between the supporting surface and the plane normal to the slope to obtain the resultant snow pressure R' (Fig. 4).

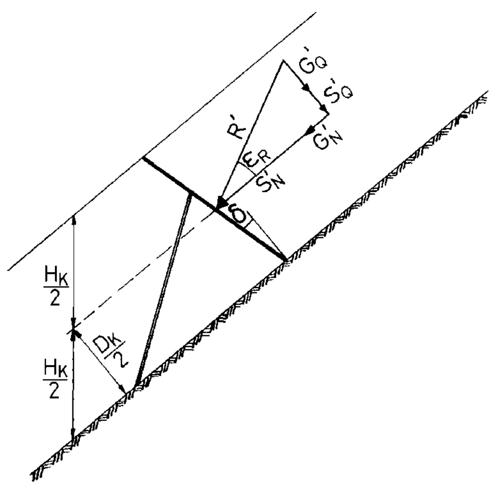


Fig. 4: Resultant snow pressure R' acting on a supporting structure.

In the revised guideline (Margreth, 2007) a new section was introduced on snow pressure on slender elements of a supporting structure. In the past years buckled supports of snow bridges were observed several times because of transverse loads due to snow masses attached to the underside of the structure (Fig. 5). The snow pressure on the supports q'_S can be assumed as a uniformly distributed line load:

$$q'_S = \eta \cdot S'_N \frac{\text{support diameter}}{\text{support length}} \cdot \sin\alpha \quad (kN\,m^{-1}) \qquad (3)$$

In Eq. (3), η is an influence factor which depends on the size of snow gliding and can be typically assumed to be 1 and α is the angle between the support axis and the surface of the ground.

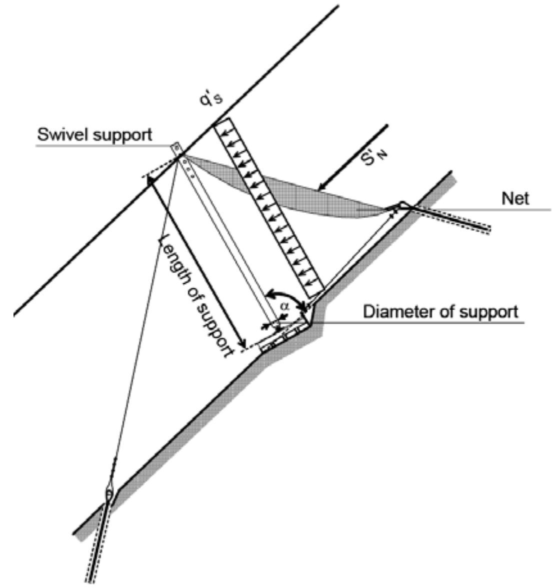


Fig. 5: Snow pressure q'_S on the support of a snow net.

5. DIMENSIONING OF SUPPORTING STRUCTURES

The design approach of the revised guidelines was adapted to the newest Swisscodes (e.g. SIA 260, 2003), which are compatible with the Eurocodes. The snow pressure loads are to be regarded as leading variable actions in verification of ultimate limit states. The design effect of action is calculated considering a load coefficient of 1.5. The design resistance is calculated considering a coefficient of resistance in relation to the chosen material (e.g. steel: 1.05 or wire ropes 1.35). Accidental design situations are not considered in the structural design.

Corrosion protection and maintenance of supporting structures are important to attain the planned service life of 80 years. In general, the superstructure needs not to be corrosion resistant. However the structure should be designed in accordance with anticorrosion principles. The foundations must be provided with corrosion protection. This can be achieved via a rust allowance of 2 mm per external surface. For anchors that are located in a chemically aggressive environment an enhanced corrosion protection with an additional sleeve pipe in plastic must be provided.

Tab. 1: Assessment of the physical condition of supporting structures

Assessment of the need for repairs and action to be taken	Effect on structural safety (maximum resistance reached and/or loss of overall stability of the supporting structure)	Time frame for appearance of consequential damage	Consequences for the viability of the supporting structure (serviceability)	Examples:
Condition Class 1 "good"				
Not urgent: keep under observation	Low	> 5 years	No impairment	Deformed crossbeams, Erosion of foundation block < 10–20 cm, Uniform surface corrosion (rust)
Condition Class 2 "damaged"				
Moderately urgent: repair within 1–3 years	Average	2–5 years	No immediate impairment	Slightly deformed supports, Displaced cable clips, Micropile anchors pushed into the ground, Exposed anchors > 20–40 cm (still intact)
Condition Class 3 "poor"				
Very urgent: immediate repairs or replacement before the winter	Large, danger of collapse	1 year	Extreme impairment: supporting function nil or very limited	Buckled supports, Heavily deformed or broken girder, Broken or pulled out anchors, Buckled micropiles, Broken wire ropes

Normally, the structures should be inspected visually once yearly and in detail every 3-5 years or after each major loading. The revised guideline includes a table to assess the physical state of supporting structures with propositions for the required actions (Tab. 1).

6. LOADS ON THE STRUCTURAL SYSTEM

The following load cases are distinguished for the dimensioning of supporting structures:

- Load case 1 assumes that the structure is subject to full snow pressure loading (Fig. 6). A snow density of 270 kg/m^3 is chosen. The snow pressure is calculated according to formulae (1) and (2). For a standard situation with a slope inclination of 45° and an altitude factor f_c of 1.1 corresponding to 2000 m a.s.l the snow pressure S'_N of formula (1) is simplified in the guidelines to:

$$S'_N = H_K^2 \cdot N \cdot f_c \quad (\mathrm{kN\,m^{-1}}) \quad (4)$$

- Load case 2 assumes partial snow loading of the structures with 77% of the structure height. The resultant snow pressure has the same magnitude and direction as with load case 1 however an increased density of 0.400 kg/m^3.
- With finite width of the supporting surface, incremental end-effect loads occur because the snow can flow laterally around the surface. The snow pressure loads are typically increased at the end of the structures by a factor of 2.5 for a distance of 2 m between the structures and maximally by 4.125 for separated structures.

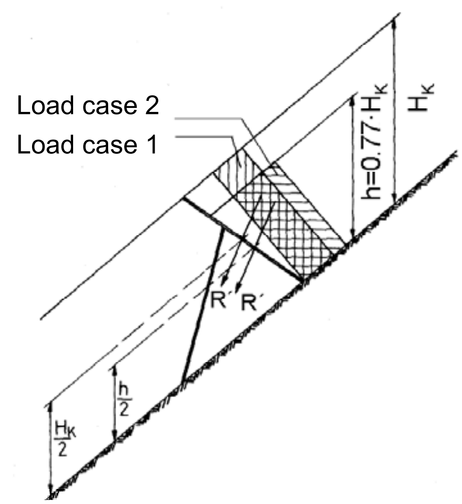


Fig. 6: Snow pressure distribution for the two load cases.

- Further additional loads such as snow pressure on supports (Fig. 5), lateral loads and lifting loads due to wind effects have to be considered.
- The grate of supporting structures is calculated with the specific loading p_H of load case 2. For a grate height D_k of 4.0 m and a glide factor N of 2.5 p_H is 29.8 kN m^{-2}.

According to the guidelines (Margreth, 2007) the layout of the supporting structure may be chosen at will. The structures should be supported on statically determined bearings. Steel bridges have a supporting surface, which is inclined typically by 15° in the downslope direction compared to the plane normal to the slope. Steel bridges are built today with one support as a three-hinged arch or with two supports forming a stiff triangle. Snow nets consist typically of triangularly shaped wire rope nets fixed to swivel posts. Because of their flexibility the snow pressure can be reduced for the dimensioning by a factor of 0.8. Tab. 2 shows typical foundation loads of different types of supporting structures.

7. EXECUTION AND DIMENSIONING OF THE FOUNDATIONS

For permanent supporting structures in loose ground, the foundations may consist of anchors, micropiles, prefabricated foundations (ground plates, Fig. 7) or concrete foundations. Until 1980 solely ground plates and concrete foundations were applied. These foundations types were uneconomic, especially for the transmission of tension forces. That is why in the 1990 guideline the application of drilled anchors and micropiles were introduced.

Ground plates are today widely applied for the transmission of pressure loads. The revised guideline allows a position of the ground plate on the surface of the ground if the angle between the direction of the support force and the surface is bigger than 75°. This rule allows the use of ground plates for the foundation of the supports of snow nets. If the angle is less than 75° the ground plate must be completely interred beneath a surface zone of at least 0.5 m (Fig. 7).

The revised guideline (Margreth, 2007) first gives values for the ground resistance. The ground resistance depends strongly on the inclination of the ground plate. The ground resistance parallel to the slope is 40% of the ground resistance normal to the slope. Experience with avalanche supporting structures shows that a ground resistance normal to the slope between 500 kN m^{-2} and 1000 kN m^{-2} may be expected. The verification of ultimate limit state of ground plate foundations is made with a total safety of 2.

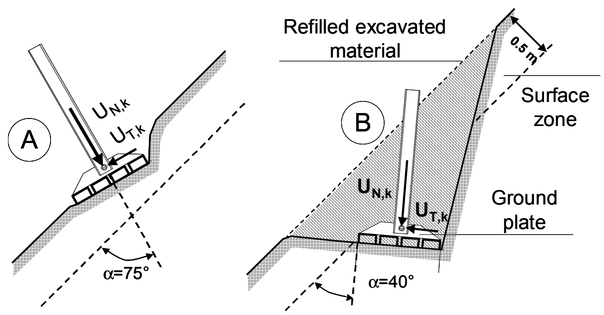
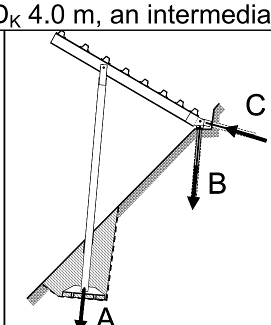
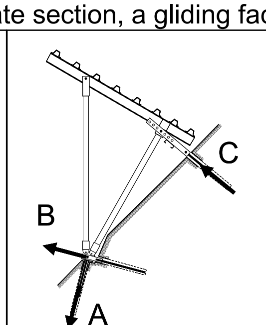
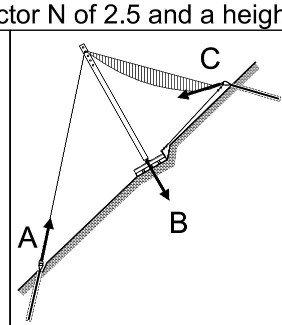


Fig. 7: Ground plate foundations (A) with $\alpha >$ 75°on the surface and (B) with $\alpha<75°$ below a surface zone of 0.5 m and refilled excavated material.

Anchors are drilled, slender, load-bearing elements, designed to withstand tension. For the purposes of the presented guideline they require a minimum diameter of the borehole of 90 mm, they should not be inclined less than 15° to the horizontal and the grout cover of the anchor bar must be a minimum of 20 mm thick. For a long service life of anchors the grouting is very important. This is why a special chapter on anchor grout is introduced in the revised guidelines. The anchor grout must be frost resistant and needs to attain a compressive

Tab. 2: Foundation forces for 3 different types of supporting structures. The forces are calculated for a structure height of D_K 4.0 m, an intermediate section, a gliding factor N of 2.5 and a height factor f_c of 1.1.

			
Snow pressure	93 kN/m‘	93 kN/m‘	85 kN/m‘
Pressure force (+) Tension force (-)	+261 kN (A)	+365 kN (A)	-81 kN (A)
	+115 kN (B)	-44 kN (B)	+255 kN (B)
	-182 kN (C)	-169 kN (C)	-322 kN (C)
Influence width	3.0 m	3.0 m	3.5 m

strength of minimally 35 N mm^{-2} after 28 days. The test of conformity during the grouting work at the site is very important. The frequency of tests should be proportionate to the quantity of grout processed, the importance of the site and the experience of the contractor. The quality of the fresh grout can be assessed by measuring the air void content (Fig. 8).

The pull-out resistance of anchors has to be determined by anchor tests. For the purpose of a pre-dimensioning the revised guidelines gives characteristic pull-out resistance in relation to the anchor length and three soil categories (Fig. 9). Typical anchor lengths vary between 3 and 10 m.

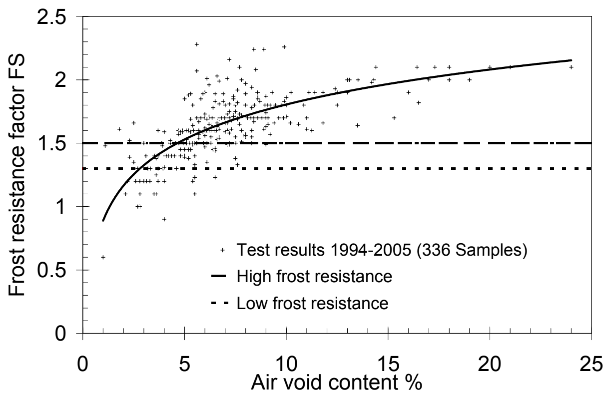


Fig. 8: Relation of the frost resistance to the air void content of the fresh grout. The diagram shows results from field and laboratory tests. If the air void content is higher than 4-5% then the grout has a sufficient frost resistance.

Micropiles can sustain pressure forces acting in the axial direction. The resistance under pressure is 50% higher than under tension. To increase the buckling resistance of the slender micropiles their heads have to be reinforced at least 1.5 m by means e.g. of stiffening pipes or concrete socles. Experience has shown that the application of micropiles in loose ground is questionable if the direction of the compression load is variable e.g. swivel supports of snow nets. That is why the revised guideline points out to preferably use concrete foundations or ground plates instead of micropiles in such situations.

8. AVALANCHE DEFENSE IN PERMAFROST

The main problems to use supporting structures in permafrost ground are creep movements, rock fall and the construction of the foundations in frozen ground (Phillips et al 2003). The inspection of the ground and the sure identification of permafrost before construction work starts are

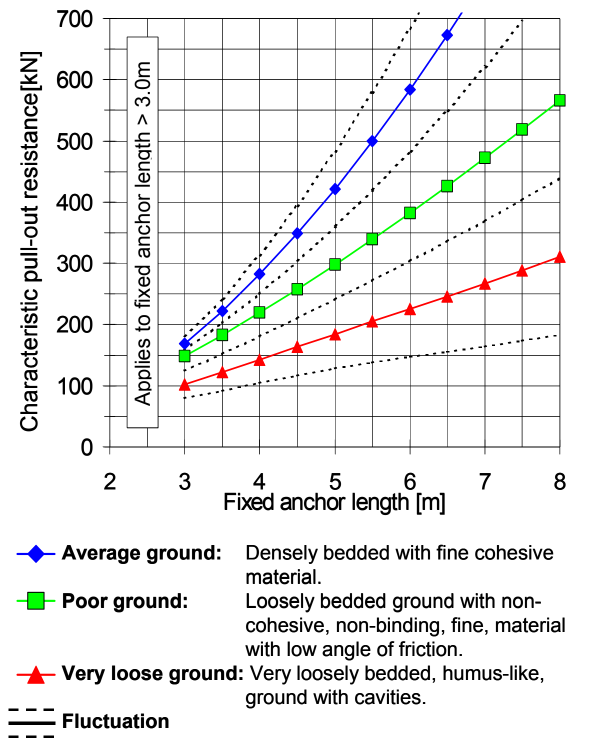


Fig. 9: Characteristic pull-out resistance of anchors as a function of anchor length and ground category.

very important. In slopes with heavy creep of more than 5 cm per year supporting structures should not be erected. Experience has shown that flexible snow nets are more suited in permafrost ground than rigid steel bridges (Fig. 10). The anchoring in permafrost is demanding because the ground quality is often poor and conventional drilling methods fail. Normal anchor grout is not permissi-

Fig. 10: Snow nets built in a starting zone with permafrost. Snow nets are less sensitive to creep movement than rigid snow bridges (Wisse Schjien, Randa, Switzerland).

ble. Special anchor grout approved under permafrost conditions can be applied down to a ground temperature of –4°C provided that the grout is preheated to 20°C before filling.

9. TYPE APPROVAL OF SUPPORTING STRUCTURES

The guideline (Margreth, 2007) specifies in Switzerland the requirements when applying for federal subsidies for avalanche supporting structures. The structures and anchor grouts must be officially tested and approved. The Federal Office for the Environment (FOEN) performs administration of the type approval procedure. The SLF and the Expert Commission for Avalanches and Rockfall (EKLS) carry out the type approval procedure. The SLF checks the static calculations and planning documents and the EKLS performs a practical utilization test. The FOEN maintains a type approval list with all approved structure types. In 2008 a total of 14 structure types from 9 suppliers are approved.

10. CONCLUSION

The revised edition of the guideline (Margreth, 2007) allows the correct application of supporting structures to reach a long service life. The experience with the guideline in regard of the structural design and the effectiveness of supporting structures are very positive. Yearly damages are by the majority smaller than 0.5% of the investment cost and the release of large avalanches in starting zones protected according to the guidelines are very seldom. It is important that the whole starting zone is covered with supporting structures.

One of the crucial points in regard of the effectiveness is the determination of the proper structure height. In the last years it could be observed that the structure height was mostly determined according to experience, without on-site snow depth observations. We encourage the project engineers to carry out more local snow depth measurements.

The calculation of snow pressure and the determination of the distance between the structures are based on quite old theories. The main goal is to provide easy applicable formulae to the engineers. It might be worth verifying or improving the theories with advanced numerical snowpack models.

The future challenge with regard to snow supporting structures consists mainly in maintaining the existing structures in an optimal way. An important point is the temporal behavior of the bearing capacity of anchors and micropiles. Maintenance and replacement concepts are needed.

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