SNOW NETS INSTALLED IN WESTERN NORTH AMERICA AND DESIGNED ACCORDING TO THE SWISS GUIDELINE

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ABSTRACT: Snow supporting structures are commonly used in the Alps to prevent the detachment of avalanches. The goal of these structures is to prevent avalanches being triggered or, at least, to prevent snow movements that could potentially lead to damage. The snow supporting structures are not designed to stop an avalanche during its motion, but, they are developed to contain the slow initial movements of the snow creating an “upslope back pressure zone” parallel to the slope. This zone is characterized by very high compression stresses. For this reason, snow supporting structures must be installed in the avalanche starting zone. Several types of snow supporting structures, approved by the Swiss Federal Institute for Snow and Avalanches Research (SFISAR) of Davos, are available in the market: snow nets, snow bridges, snow rakes. It is nowadays evident the increasing of snow net types, which are light and environmentally friendly structures composed by triangular net panel supported by steel tubular struts and bracing cables fixed to the ground by anchoring systems. These structures are designed in fully accordance with the technical Swiss Guideline (2007), thus, assuming the typical average snow density of the Alps (approx. 270 kg/m³). Whenever snow nets are foreseen in areas with characteristics different from the one recorded in the Alps, designers must adapt their snow supporting structures to the new environment. This paper describes some criteria that should be adopted during design and installation phases in order to adapt the standard structures to the Western North American snow conditions, which are characterized by an average snow density while higher (approx. to 400 kg/m³ - 500 kg/m³) than the one measured in the Alps. An actual experimental case study is presented to underline the measures considered along the Highway Interstate 190 at Snoqualmie Pass (Washington, USA).

KEYWORDS: Defence structure, snow supporting structure, avalanche protection, snow net, Swiss guideline, North Western America.

1 INTRODUCTION

An avalanche is a mass of snow and/or ice falling rapidly down a mountainside, progressively swelling its volume and dragging down with it everything in its path.

The behaviour of the snow pack is similar to a viscous fluid characterized by a high density. The density defines the weight (driving force) and consequently the slide of the snow. The proprieties of the fluid depend basically on the temperature and the type of movements and stresses that occur within it. Compression, traction and shear stresses are developed in the snow pack. These stresses affect the movements and the deformations of the snow, and they define the possible collapse and consequently the type of avalanche. The snow pack is a non-homogeneous and anisotropic body because it is generally composed of different layers. Its sliding and glide velocity, which define the shear stress, can vary between layers. Moreover, the snow pack can modify its mechanic characteristic in function of the temperature.

The snow cover moves constantly and slowly toward downslope, and it is possible to define 2 main movements (Figure 1):

1. Creep: it is due to the weight of the snow, which defines the settlement and the shear deformation parallel to the slope;

2. Glide: it depends on the type of soil (roughness) and on the possible water presence at the interface between the soil and the snow. It is the downslope motion of the snow pack.

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Figure 1. Glide and creep velocity in the snow pack. Where: \( w \) = creep velocity normal to the slope; \( \mathbf{u}_g \) = glide velocity; \( u \) = velocity component parallel to the slope (shear); \( v \) = resultant velocity vector. (Reference Fig. 4 of the Swiss Guideline, 2007)

For the most part, every avalanche area consists of 3 distinct zones:
- Detachment zone (starting zone): it is the area where the avalanche originates. Normally, it is defined above the tree line, or by the mountain crests or ridges, or where there is a snow accumulation due to new snow falls or wind effect (snow drifts). In this area the unstable snow starts to move downslope. Creep movement and consequent glide mechanism can occur at the ground surface level. Movements depend on several factors, such as: slope inclination (generally between 30 and 50 degrees), snow thickness, soil roughness, snowpack characteristics (SWE, internal friction, unit weight, plasticity, etc.), wind effects and sun exposure, etc.
- Sliding zone: it is the area between the starting zone and the run-out area. In this zone the avalanche reaches its highest velocity. This area is normally characterized by high inclination and low presence of vegetation.
- Run-out zone (stopping zone): it is the area where the avalanche reduces its velocity and stops its motion. In this zone high pressures may occur.

2 SNOW SUPPORTING STRUCTURES

Snow supporting structures are able to avoid the starting of the avalanche. For this reason, they are placed in the detachment zone in order to reduce snow movements and consequently prevent the avalanche detachment.

Table 1 presents the main types of snow supporting structures available in the market. All these systems can be designed with either steel or wood or combined (wood and steel) elements. The type of system must be chosen considering different aspects, such as the morphology of the slope, the snow characteristics, the allowable risk, the importance and type of structures to be protected, etc. Thus, designers must know all advantages and disadvantages of the different structures in order to guarantee a suitable and safe design. These supporting structures have the function to withstand mainly the static snow pressure but also the possible dynamic forces due to little snowpack movements.

<table>
<thead>
<tr>
<th>Type of structure</th>
<th>Description</th>
<th>Example</th>
</tr>
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<tbody>
<tr>
<td>Rigid</td>
<td>When the creep and glide motions of the snow are arrested by a structure subjected to only slightly elastic deformations.</td>
<td>Snow Bridges, Snow rakes</td>
</tr>
<tr>
<td>Flexible</td>
<td>When the structure is able to follow and adapt itself to the snow movements (up to a certain level).</td>
<td>Snow nets</td>
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For particular applications snow supporting structures can be combined with other helpful interventions such as:
 a) modifications of the ground in order to increase the roughness of the slope and consequently reduce the possibility of the avalanche detachment;
 b) structures (i.e. wind deflectors, or snow fences) able to control and modify the wind flow in order to avoid the formation of dangerous snow accumulations and/or snow ledges.

3 SNOW NETS

As mentioned in the previous paragraph, several types of snow supporting structures are available in the market: snow bridges, snow rakes, snow nets. It is nowadays evident the increasing of the number of snow nets (Figure 2).
Snow nets (Figure 3) are composed of triangular net panels supported by steel posts and down-slope bracing cables fixed to the soil by anchoring systems (generally flexible double-legs cable anchors). Posts are connected to the ground by foundations that can vary depending on the type of soil: generally micropiles are used on rock, micropiles plus steel bars are used for rock and hard soil, concrete plinths that may be also coupled with micropiles and/or steel bars are used for loose soil, and big steel plates plus cable anchors are used for weak soils or permafrost.

Table 2 shows the advantages and the disadvantages of snow nets.

4 THE SWISS GUIDELINE

The Swiss Guideline (Defence structures in avalanche starting zones – Technical Guideline as an aid to enforcement), issued in 2007 by the Swiss Federal Institute of Snow and Avalanche Research of Davos (SLF), represents worldwide the milestone for projects of snow supporting structures installed in the avalanche starting zone. The guideline defines all aspects and procedures to plan the design of a snow supporting structure. Moreover, it defines which must be the components of the structure, how to define the acting loads, how to design from a structural point of view the avalanche protection and which are the foundations/anchors typologies and the grout requirements to adopt.

As mentioned in table 2, snow nets can be certified by the SLF and consequently homologated by the FOEN (Federal Office for the Environment of Bern). These specifics certification and approvals are obtained by the manufacturers of snow nets that design their structures according to the Swiss Guideline. All the homologated structures are listed in the official FOEN website by downloading the Typenlist Lawinenverbauungen (www.umwelt-schweiz.ch/uv-1006-d), which is the official list of the only snow supporting structures allowed to be installed in Switzerland.

Table 2. Strengths and weaknesses of snow net supporting structures

<table>
<thead>
<tr>
<th>Features</th>
<th>Description</th>
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<tr>
<td>Advantages</td>
<td>- Adaptable to the acting loads thanks to their flexibility (within certain limits); - Lightweight structures; - No interruption of the snow pack continuity; - Can withstand little rockfall impacts; - Adaptable almost to any slope morphology; - Environmentally friendly due to their low visual impact; - Can be certified by the SLF and approved by the FOEN.</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>- If damages occur, the maintenance of certain elements can be complex; - High maintenance required; - Requirement of specialized expertise for in-situ staking out operations (layout of upslope and downslope anchors and post foundations); - Specialized crew is required for the installation; - High forces acting on anchoring elements (not recommended for D0 &gt; 4,0 m and for very loose soil); - Forces on the structure depends on the sag of the triangular net: during the installation and after every winter the sag must be checked; - The design has to be carried out by experts.</td>
</tr>
</tbody>
</table>

The SLF of Davos (Switzerland) is worldwide recognised as the most famous and prestigious research centre in the snow and avalanche field. To obtain the approval (homologation) of a snow net supporting structure, manufacturers must follow the following steps (Castaldini, 2010):

1. Preparation of a detailed documentation stamped by a professional engineer with: structural calculation of all the elements of the structure, detailed drawings and installation manual;
2. Get the documentation across the FOEN of Bern. The SLF verifies the calculation of all the elements constitute the snow net, according to the Swiss Guideline (2007). Moreover, the SLF analyses the types of foundations...
The design of snow supporting structures must take into consideration several important aspects which are codified by the Swiss Guideline, such as:

- Inclination of the slope in the detachment zone (max value): $\psi$;
- Glide factor, which depends on the roughness of the soil and the sun exposure: $N$. In the Alps this value is between 1.2 (no sun exposure and high roughness) and 3.2 (sun exposure and low roughness);
- Altitude coefficient, which depends on the elevation of the site above the sea level: $f_c$. In the Alps it is assumed between 1.0, if the elevation is equal or lower than 1,500 m a.s.l., and 1.3, if the elevation is more than 3,000 m a.s.l.;
- Effective thickness of the net: $D_k$. It is the snow thickness measured perpendicular to the slope (i.e. $D_k = D_K \cos \psi$ (3))
- Minimum lateral distance between the structures along one alignment: $A$;
- Average snow density: $\rho = 270$ kg/m$^3$. This value is obtained considering the average unit weight of the snow in the Swiss Alps at an altitude of 1,500 m a.s.l. and an exposure of the slope WNW-N-ENE.

Here below are presented the most general formulas (Margreth, 2008) to define the pressures acting on the structure (section 4 of the Swiss Guideline). These stresses depend on creep and glide movements and are at the base of the dimensioning of the structure. Even if these formulas represent the simplification of the real snow behaviour, they are clear and easy to use. Moreover, in-situ experience shows that these equations give reliable results.

The components of the specific snow pressure parallel and perpendicular to the slope can be calculated as (per linear meter of structure):

\[ S'_N = \frac{1}{2} \rho \cdot g \cdot H^2 \cdot K \cdot N \cdot f_s \cdot f_c \]  
\[ S'_Q = S'_N \cdot a / (N \cdot \tan \psi) \]  

Where:
- $\rho$ = snow density;
- $g$ = gravitational acceleration;
- $H$ = vertical snow thickness
- $K$ = creep factor (function of the snow density and the slope inclination);
- $N$ = glide factor (function of the class of the ground and exposure);
- $f_s$ = reduction factor for a flexible supporting structure (usually for snow nets in the Alps is 0.8, while for rigid structures is 1.0);
- $f_c$ = altitude coefficient (function of the altitude above sea level; it varies from 1.0 to 1.3)
- $a$ = factor that depends on the snow characteristics (it varies between 0.2 and 0.5)
- $\psi$ = average slope angle.

Both these pressures are assumed to be distributed uniformly along the entire height of the structure. This is a strong generalization because the pressure into the snow cover is extremely complex, even if the snow pack is quite homogeneous: formula (1) is the simplification of complex differential equations of the snow pack.

Usually, in accordance with the Swiss Guidelines, the component $S'_Q$ is neglected for snow net designs. However, it has to be underlined that for no-Alps conditions, the $S'_Q$ value can be different from 0, thus it may be necessary to consider it during the calculation.

At this point it is possible to identify the incrementing load due to the fact that the snow supporting structure is not perpendicular to the ground surface, thus the weight of the snow prism formed between the supporting structure and the normal to the surface has to be considered.

\[ G' = \frac{1}{2} \rho \cdot g \cdot D^2 \cdot \tan \delta \]  

Where:
- $D = $ snow thickness measured perpendicular to the slope;
- $\delta = $ angle between the structure and the perpendicular to the slope.

The parallel and the normal component of $G'$ are respectively:

\[ G'_N = G' \cdot \sin \psi \]  
\[ G'_Q = G' \cdot \cos \psi \]  

The marginal forces (Figure 4) that act at the extremities of a row of the structure can be
taken into account with the following equation (per $\Delta L$ of structure):

$$S'_R = f_R \cdot S'_N$$

Where:
- $f_R$ = marginal factor, which depends on the lateral distance between the structures ($A$) and the coefficient $N$;
- $\Delta L$ = length where $S'_R$ is acting, it depends on $A$.

Finally, it is possible to obtain the resultant forces acting on the structure in the different section of the snow supporting system: intermediate (MF), interval (RF) and end (WF).

$$R'N_{MF} = S'_N + G'_N + W'_N$$

$$R'N_{RF} = S'_N + G'_N + W'_N + S'_R_{RF}$$

$$R'N_{WF} = S'_N + G'_N + W'_N + S'_R_{WF}$$

$$R'Q_{MF} = R'Q_{RF} = R'Q_{WF} = S'_Q + G'_Q + W'_Q$$

The weight of the structure, $W$, is usually negligible for the snow net calculation.

5 SNOW NET APPLICATION IN NORTH WESTERN AMERICA

As described in the previous paragraph, standard snow nets are designed using standard parameters defined by the Swiss Guideline (2007). In the case where in-situ local parameters differ from the ones adopted in the calculation, it is necessary to check the compatibility and, if necessary, design the structures ad hoc (customization). In this way, snow supporting structures will be able to withstand the new larger forces and pressures acting on them.

In Alps environments the parameters that can vary are generally: the inclination of the slope, the glide factor, the altitude and the snow thickness, while the average snow density is generally considered constant (approx. 270 kg/m$^3$).

The situation is different in Western North America (Pacific Coast of Canada and the U.S.A.) where the snow might have an average density resolutely higher than the one measured in the Alps: it is not unusual to have average snow density of 400 to 500+ kg/m$^3$. This fact is due to the presence of the Pacific Ocean which defines gentle and raining winters. Warm temperatures at low elevation and frequent rainfalls on the snowpack increase the snow humidity and SWE and consequently the snow unit weight rises. As per consequence of the snow density increment, snow supporting structures are stressed by loads higher than the ones used to obtain the WSL and FOEN approvals.

Figure 5 shows that the component parallel to the slope of the specific snow pressure ($S'_N$) increases if the average snow density ($\rho$) increases as well. These increments follow a parabolic behaviour. It is possible to underline that with the rising of $\rho$ the different curves (one for each $Dx$) diverge. Thus, it is evident that the $S'_N$ is not directly related to the snow unit weight: a little variation on the average snow density can induce a big change on the snow pressure. For instance, by increasing the snow density from the typical value of the Alps (270 kg/m$^3$) to the one recorded in the Western North America (400 to 500+ kg/m$^3$, depending on the zone), the value of the snow pressure $S'_N$ almost redoubles.
(i.e. for a snow supporting structure $d_k = 3.5$ m with an average snow density equal to 450 kg/m$^3$, the $S_N = 133$ kN/m', instead of 68 kN/m', that is the value for the Alpine average snow density assumed equal to $270$ kg/m$^3$).

Consequently, the structures are stressed with higher loads, which can cause damages or failures. For these reasons, it is necessary to calculate the loads on snow nets in the real conditions and to proceed with a customization of the design of the structures for the specific case.

Two measured may be adopted to reduce the possibility of unpleasant structural collapses:
1. To increase the dimension of the single elements of the structure;
2. To adapt the snow net and the site conditions in order to reduce the pressure on the structure.

6 CASE STUDY

Snoqualmie Pass is located approx. 80 km east from Seattle (WA, USA), at approx. 3022 feet (921 m a.s.l.) in the Cascades Mountains (Figure 6). This mountain area is characterized by really wet snow falls due Pacific Ocean influence. Moreover, snow falls are constant during the winter (November to April), and the thickness of snow accumulated during the season can reach really high values (up to 450 cm) (Stimberis et al., 2009). Typical traffic volumes over Snoqualmie Pass are about 28,000 vehicles per day and about 5,600 of those vehicles are trucks (data from WSDOT). During winters, the Snoqualmie Pass is subjected to closures and delays due to the weather conditions, avalanches, avalanche controls, etc. (Castaldini et al., 2013).

This project is also one of the largest in a maritime climate and, at the moment, the first for importance in Western North America.

The most persistent avalanche zones through the Snoqualmie Pass are on the east side of the summit, along Lake Keechelus (Figure 7). Four potential avalanches detachment areas have been identified (from west to east):
- East Shed Minus One;
- Bald Knob;
- Slide Curve;
- Sector Fourteen.

The Final Design Recommendations (Mears et al., 2010) specified the installation of snow nets approved by Swiss Federal Institute for Snow and Avalanche Research (SFISAR) of Davos and manufactured in full accordance with the specifications of the Swiss Guideline. Maccaferri flexible standard snow nets have been chosen during the design in order to protect the highway against the snow avalanches phenomena. These structures have been approved by WSL according to the Swiss procedure described in paragraph 4.

Considering that these structures have been calculated using the typical parameters of the Alps, several aspects had been taken into consideration during the design in order to check their ability to withstand the real loads defined by a completely different environmental condition.

For the specific case, the data provided with the preliminary design were:
- The average snow density equal to 400 kg/m$^3$ (148% higher than the typical value of the Alps);
- The snow height was defined in 2 different values: $H_k = 3.5$ m, below 850 m a.s.l., and $H_k = 4.5$ m, above 850 m a.s.l.

Furthermore:
- The roughness of the slope, in several spots was really low;
- The presence of steep, smooth and wet rock outcropping surface was remarked;
- The high probability of rainfalls on the snowpack could cause the formation of a layer of water at the interface rock-snowpack;
- The low altitude could cause an increasing of the snowpack temperature (close to melting point), which can decrease the shear resistance inside the snowpack;
- Rockfall phenomena could occur at the top of Slide Curve.

All these conditions listed above increase the pressure and the forces acting on the standard systems. In order to reduce the stresses on structures and the risk of structural failures, some modifications on the site and on the snow nets have been adopted.

First of all, in the upper part of Slide Curve, the rockfall hazards have been reduced in order to avoid any rock impact against the snow nets. Scaling and blasting were imposed to eliminate the most dangerous unstable rock blocks. Moreover a simple drapery system with cable panels coupled with hexagonal double twist wire mesh was designed in order to contain the possible rock falls.

After accurate and specific calculations, stronger types of standard snow nets, with higher $D_k$ and/or higher $N$ value were suggested. These structures were able to withstand higher loads and thus reduce the risk of failure. Snow nets with $D_k = 3.5 \text{ m} N = 3.2$ (East Shed, Bald Knob and Sector Fourteen) and $D_k = 4.0 \text{ m} N = 3.2$ (Slide Curve) were planned instead of using respectively $D_k = 3.0 \text{ m} N = 3.2$ and $D_k = 3.5 \text{ m} N = 3.2$, as per the input data of the original design. In the lower part of Slide Curve $D_k = 3.0 \text{ m} N = 3.2$, was planned instead of $D_k = 3.0 \text{ m} N = 2.5$ as per the input data of the original design. Some benches were realized in the lower part of Slide Curve, characterized by material accumulated consequently to landslide and scaling: debris, rolling stones and big boulders, in order to allow the installation of the expected snow nets, otherwise not possible.

Then, in very smooth surfaces, in order to increase the roughness of the slope, prevent the snow glide (Stimberis et al., 2008) and reduce the loads on the snow nets, several lines of wood (or steel) “sleeves” were defined (Figure 7). These sleeves are composed by wood logs (or steel pipes) with a diameter of approx. 40 to 50 cm, disposed horizontally and perpendicular to the possible snow glide. They are anchored to the rock by flexible cable anchors disposed every 2.0 to 2.5 m and calculated ad hoc for the specific site. For instance, the rows of sleeves were defined in the upper part of Slide Curve (Figure 8), in Sector Fourteen and strongly suggested in East Shed and Bald Knob areas. These rows have to be placed at no more than 2.0 to 3.0 m from the upslope anchors of the snow nets, and with a distance of approx. 3.0 m between each other. The length of each sleeve depends on the local morphology and it can vary between approx. 4.0 and 5.0 m. The number of lines of sleeves has to be defined on site during the installation. At the time of writing, the structures to increase the slope roughness are not installed yet. It is clear that, the higher number of lines of sleeves is placed, the greater will be the effectiveness increase of roughness and the consequent reduction on the gliding effect on the snow nets.

Additionally, in East Shed, Bald Knob and Sector Fourteen, in order to take into consideration the presence of very smooth zones and the possible high glide due to the water presence at the interface rock-snowpack, the reduction factor ($f_s$) was increased from its standard value 0.8 to 0.95.

Furthermore, for each site, an altitude factor ($f_c$) of 1.1 has been assumed instead of the standard 1.0.

Finally, in all sites, in order to reduce the effects of the snow pressure against the snow nets, the distance between the structures was
reduced of approx. 10% as per the Swiss Guideline recommendations.

At the present, approx. 200 linear meters (post-to-post distance) of snow nets is already installed in East Shed (164.5 m) and Bald Knob (31.5 m) by Hi-Tech Rockfall Construction Inc. The installation productivity was approx. 20 to 30 m/day with a crew of 5 people (only for the elevation of the structures – no anchors and foundations). The project is still on going and, by the summer 2015, it is planned the installation in Slide Curve (approx. 780 m) and Sector Fourteen (approx. 164.5 m) too, for a total of approx. 1,200 m of structures in the 4 areas.

7 CONCLUSION

The prevalence of snow supporting structures, such as snow nets, has continued to rise over the last few 10-years to protect ski resorts, villages and infrastructures. This phenomenon is linked to the high performances of these type of structures, as well as their cost-efficiency. The Swiss Guideline (2007), defines all aspects and procedures to design snow supporting structures. This guideline is nowadays recognized worldwide. Standard snow supporting structures, approved by the Swiss Federal Institute for Snow and Avalanches Research of Davos, are calculated based on snow characteristics and environmental conditions of the Alps (generally characterized by an average snow density of approx. 270 kg/m$^3$). These are completely different from the one remarkable in Western North America (Pacific Coast of Canada and the U.S.A.), characterized by very wet snow (average snow density up to 400 to 500+ kg/m$^3$). The main consequence of this snow density increment is a considerable increase of the snow pressure acting on the structures (i.e. for a snow supporting structure $D_N = 3.5$ m, the parallel component of the snow pressure $S'_{N}$ can rise of approx. 62%, by moving the average snow density from 270 kg/m$^3$ to 400 kg/m$^3$). A real case study of snow nets design to protect the Highway I-90 at the Snoqualmie Pass (Washington State – USA), is presented.

The paper described the design procedure and the in-situ precautions adopted in order to reduce the stresses on the structure and to be able to use the standard snow supporting structures in an environment completely different from the Alps. Snow nets at the Snoqualmie Pass have been designed and installed considering certain input data and assumptions. This project can be considered as “experimental”, because at the present it is not very well know the behaviour of these type of structures in North Western America environments. One of the main reasons is poor presence of snow supporting structures and particularly snow nets in this part of the world. Another reason is due to the fact that the typical snow of these areas is very wet, with a high percentage of water due to the temperatures close, or just below, the snow melting point. This condition increases the average snow density and the stresses (forces and pressures) acting on snow supporting structures.

In conclusion, it is important to underline that only winters (Figure 9) can give an answer about the real behaviour of these snow nets set up in these extreme conditions. Nevertheless it is important to understand that snow nets have to be constantly monitored and maintained in order to minimize any possible structural problem.

Figure 9. Check of the different snow nets after the first winter – May 2014, Bald Knob.

8 REFERENCES


CONFLICT OF INTEREST

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