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Interaction of flexible rockfall barriers with avalanches and snow pressure

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Abstract

Rockfall barriers are optimized to absorb high punctual impact energies. In mountain areas the barriers are also loaded by avalanches and snow pressure. Snowpack forces and dynamic avalanche pressures act over a much larger area and over longer time periods. Thus, if not properly designed, rockfall barriers can be damaged. In winter 2003–2006 we investigated the interaction of flexible rockfall barriers with avalanches and snow pressure on a study site in Fieberbrunn, Austria and in other areas. In several locations the barriers successfully stopped small wet snow avalanches. However, the main problem turned out to be the insufficient retention capacity during the whole winter and the structural behaviour. The weakest points are the retaining ropes and the post foundations. For an appropriate design of the barrier the main input factors determining snow pressure and avalanche pressure have to be assessed.

Keywords: Avalanche protection; Rockfall barrier; Avalanche dynamics; Snow pressure

1. Introduction

In the last 10 years the behaviour of rockfall barriers has been studied with full scale tests. The result of these tests was an optimized generation of flexible ring net barriers which absorb impact energies of up to 5000 kJ. The energy is mainly dissipated by the ring net and brake devices (Gerber et al., 2003). Flexible barriers are widely applied to protect settlements and traffic lines from rockfall. However, in mountain areas with an abundant snowpack, the flexible barriers are also loaded by avalanches and snow pressure. A rockfall event produces a large dynamic load on a relatively small barrier area. The interaction of the snowpack and avalanches with the barriers is very different. Snowpack forces and dynamic avalanche pressures act over a much larger area and over longer time periods (Table 1). Thus, if not properly designed, rockfall barriers can be damaged. After the successful application of flexible barriers to stop and retain debris flows (Roth et al., 2004), first trials were made to stop small avalanches. To obtain a better understanding of the interaction and performance of rockfall barriers with snow pressure and avalanches, case studies were performed in Switzerland, Germany and Austria. We summarize the data and experiences obtained.

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2. Description of the study site in Fieberbrunn

In the ski resort Fieberbrunn in the Kitzbühl Alps (Austria) the 460 m long ski run "Jägersteig" has to be closed during long periods of time every winter because of avalanche hazard. The ski run is situated below a 180 m long 40° steep slope at an elevation of 1310 m a.s.l. (Figs. 1 and 7). The slope is partly covered with deciduous trees. After each snow fall period avalanches are released artificially by explosives. The main concern is warming periods and the consequent release of wet snow avalanches, which are much more difficult to control. At the elevation of the starting zone the 100 year snow depth is estimated at 360 cm and the mean yearly new snow sum at 620 cm. A protection project with several lines of snow supporting structures was established to reduce the avalanche risk. Because of the high cost alternative protection measures in the form of rockfall barriers were proposed. The rockfall barriers should brake and catch the avalanching snow masses. In a first step it was decided to investigate the suitability of rockfall barriers to stop small avalanches in a research project funded by the Centre for Natural Hazard Management alpS.

The main goals were to study the behaviour of the structures and to optimize their resistance against snow pressure and avalanche impacts. In 2002 a 20 m (termed A) and a 15 m long barrier (termed B) of the system FATZER AG Geobrugg RX-avalanche with heights of 5 m were built in the most frequent avalanche zones 30 m above the ski run (Fig. 2). The posts and ground plates correspond to a 3000 kJ barrier and the rope assembly to a 2000 kJ barrier with an additional down slope rope. The post spacing was reduced from the normal design width of 10 m to 5 m. Because of the areal load, a weaker ring net was chosen compared to a corresponding rockfall barrier. The ring net was covered with a wire netting having a mesh opening of 50 mm. The barriers were closely monitored during winter, recording the snow distribution, the snow height with probing, the snow density and the geometry of the system by measuring the inclinations and deformations of the main structural elements. Snow data were collected daily at the nearby observation field "Kogel" at 1600 m a.s.l. and in Fieberbrunn (780 m a.s.l.). The avalanche activity in the study site was surveyed by ski patrollers.

Table 1
Comparison of different loads on a ring net barrier

Criteria	Rockfall	Avalanche impact	Snow pressure
Load distribution	Single peak load	Areal load over a part of the barrier area	Areal load over total barrier area
Impact time	0.2–0.5 s	1–5 s	Weeks–months
Deformation	5–8 m	2–3 m	1–2 m

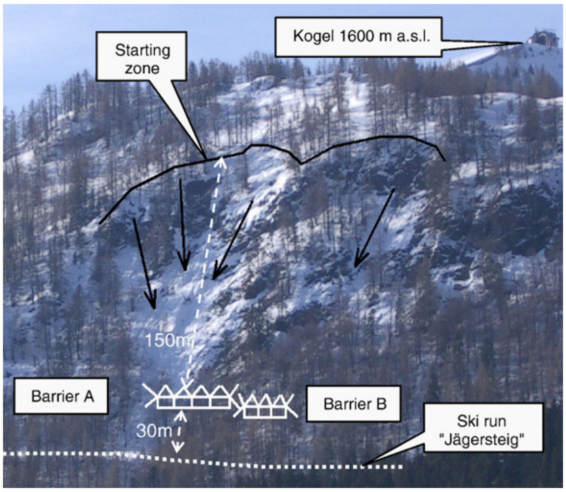

Fig. 1. Overview study site in the ski resort of Fieberbrunn, Kitzbühl Alps, Austria.

3. Meteorological and avalanche situation during the 4 test winters in Fieberbrunn

In the winters 2003 and 2006 the snow heights were slightly above average (Table 2). The first test winter had the smallest snow pack and was not very valuable for an evaluation. During the last 2 winters however large snow heights were recorded. The new snow sum of winter 2006 had a return period of estimably 10 years. In every winter at least 11 avalanche days were counted. Most of the avalanches hit the barriers. In winter 2004

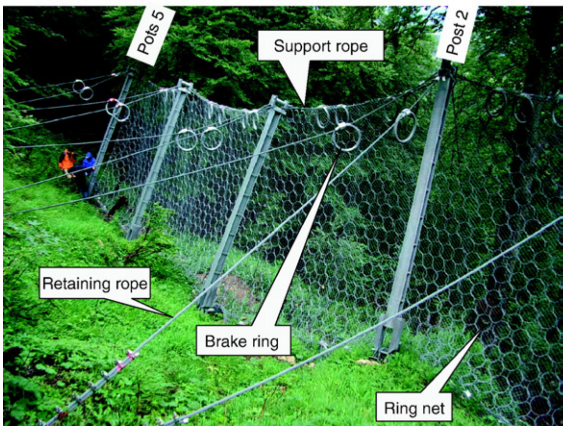

Fig. 2. Study site, RX-avalanche ring net barrier A (5 posts, total length 20 m).

Table 2
Snow data, avalanche activity and closure days of the ski run “Jägersteig”, Fieberbrunn, Austria

Winter	Fieberbrunn (780 m a.s.l.)		“Kogel” (1600 m a.s.l.)	Avalanche activity		Closure of the ski run “Jägersteig”	
	Max. snow depth	New snow sum	New snow sum	Number of days with		Number of closure days	Number of open days
				Artificial release	Natural release		
2002/2003	1.05 m	3.27 m	4.89 m	7	4	20	90
2003/2004	1.10 m	4.98 m	6.50 m	11	2	56	69
2004/2005	1.65 m	5.23 m	6.15 m	13	1	33	96
2005/2006	1.25 m	6.43 m	9.22 m	17	5	48	84
Mean value of 92 winters (1895–1999)	1.09 m	4.36 m	–	–	–	–	–

the ski way was closed on 56 days because of avalanche hazard. We summarize that the last 3 winters were valuable for testing the barriers.

4. Results from the study site in Fieberbrunn

4.1. Retention capacity

In winter 2004 and 2006 both barriers were for the most part filled to the top with avalanche deposits (Figs. 3 and 4). The highest deposits were always observed in sections where the avalanche flow was slightly canalized. In both winters barrier A was already filled at the end of January. All subsequent avalanches overflowed the net. The snow height distribution behind post 3 of barrier A is given in Fig. 5. If completely filled, the influence of the net ends after a distance of 10 to 15 m upslope. The snow depth behind the barrier was 2 to 4 times higher compared to the undisturbed area beside the barriers. The maximal deposit volume behind the 5 m high barrier was 38 m^3 per meter barrier length. With a barrier length of 20 m the total amount of stopped snow would thus be 760 m^3. This volume is very similar to observations where barriers were hit by debris flows (Roth et al., 2004). The average densities of the deposited snow were rather high, ranging from 410 to 510 kg m^{-3}. This corresponds to a densification of the new snow by a factor of 3 to 4 if a new snow density of 120 kg m^{-3} is assumed.

The surface inclination of the banked-up snow behind the completely filled barrier varied between 12° and 20° measured over a distance of 8 m. The terrain inclination is around 40°. The surface inclination of the banked-up snow determines the deposit volume. Higher inclinations correspond to a bigger deposit volume. Frutiger (1965) investigated the behaviour of avalanches in areas controlled by supporting structures. According to his observations the inclination of the banked-up snow behind the structures varied between 19° and 30°.

In winter 2006 a 5 m wide section of barrier A was not covered with a wire netting having a mesh opening of 50 mm. In this section the retaining capacity of the

Fig. 3. Barrier A in Fieberbrunn on 4 April 2005. The 5 m high barrier is completely filled with avalanche deposits.

Fig. 4. Barrier A in Fieberbrunn on 15 April 2004.

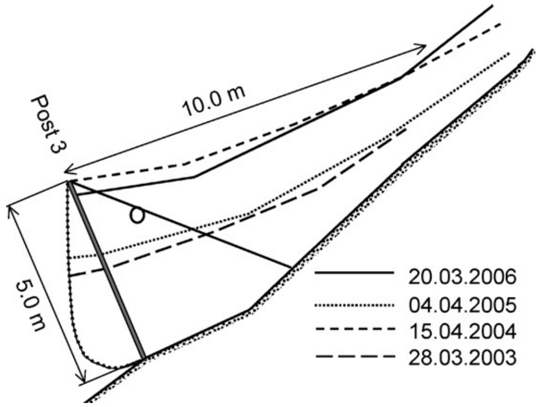

Fig. 5. Measured snow heights in the four test winters behind post 3 at barrier A in Fieberbrunn.

ring net was much reduced. The wire rings had a diameter of 300 mm. On 20 March 2006 the snow depth in this section was about 1.5 m less in comparison to the neighbouring section with a 50 mm mesh cover. This observation corresponds to former experiences (Margreth, 1996).

The retention capacity of a barrier is crucial for providing a sufficient safety against avalanches. However the total avalanche volume during the whole winter in Fieberbrunn was much higher than the retention capacity. The potential avalanche volume of a whole winter depends mainly on the new snow sum ΣHN in m for the whole winter in the starting zone, the snow densification, the length of the potential starting zone L_{hor}, the avalanche activity, the terrain roughness and the topography of the avalanche track. The total densified avalanche volume V_a per meter barrier length, which has to be stopped by the barrier, can be estimated as follows:

$$V_a = \frac{(\sum \mathrm{HN} \cdot L_{hor})}{C} \left[\mathrm{m}^3 \mathrm{m}^{-1}\right]. \quad (1)$$

The factor C describes the relation between the potential avalanche volume and the avalanche volume stopped by the barrier. The factor C depends mainly on the densification of the new snow and the local conditions:

– Terrain roughness: An avalanche loses a part of the mass before hitting the barrier if the terrain roughness is high (e.g. big boulders, trees).
– Topography: If the avalanche track is very steep then it is more likely that an avalanche will hit the barrier.
– Artificial triggering: The number of avalanche releases is increased if artificial triggering is applied in a starting zone.
– Snow stability: On steep, north-oriented slopes at high elevations the snow stability is smaller and the number of avalanche releases is higher compared to a south-oriented and low angled starting zone.

For the study site we determined for 5 dates the maximal volume stopped by the barrier and calculated the potential avalanche volume (Table 3). We used the new snow sum until to the observation date measured at "Kogel" and a horizontal length L_{hor} of 130 m according to the topographical situation. The corresponding factor C varies in a wide range between 16 and 52. For design purposes we would propose for Fieberbrunn a factor C of 10, which includes a certain safety. This factor is regarded to be rather high because of the high avalanche activity, the steep avalanche track and the low terrain roughness. With formula (Eq. (1)) the necessary retaining capacity can be determined. In order for a barrier to stop an avalanche completely, the run-up height of the snow masses during the impact has also to be considered (see Eq. (3)).

4.2. Barrier loading

The loading of the barrier due to avalanche impacts and snow pressure could be determined by analysing the deformation of brake rings of the barrier (Figs. 2 and 9). Brake rings are fundamental energy absorbing devices in rockfall barriers. They are integrated in the support ropes and retaining ropes. The tension force in the ropes is given according to the elongation of the brake elements measured in laboratory tests. The support ropes are fixed to the post alternating with wire rope clips which function as rated break points. The load distribution and static model applied for the back

Table 3
Comparison of the measured condensed avalanche volume with the potential avalanche volume in Fieberbrunn

Date of observation	Section with maximum snow height	Measured condensed avalanche volume V_a	New snow sum measured at "Kogel" until observation date	Potential avalanche volume $V_p = \Sigma \mathrm{HN} \cdot L_{hor}$	Factor C
28.03.2003	Post 3–4	10 $m^3 m^{-1}$	369 cm	480 $m^3 m^{-1}$	48
20.02.2004	Post 3	34 $m^3 m^{-1}$	410 cm	533 $m^3 m^{-1}$	16
04.04.2005	Post 3–4	14 $m^3 m^{-1}$	555 cm	722 $m^3 m^{-1}$	52
12.01.2006	Post 4	28 $m^3 m^{-1}$	430 cm	559 $m^3 m^{-1}$	20
20.03.2006	Post 4	38 $m^3 m^{-1}$	825 cm	1073 $m^3 m^{-1}$	28

calculation of the avalanche impact and snow pressure is given in Fig. 6.

4.2.1. Avalanche impact

The perpendicular impact pressure from a dense flow avalanche on a large rigid obstacle can be calculated by:

$$p_N = \rho \cdot v^2 \quad (2)$$

where p_N is the pressure in N m^{-2} perpendicular to the impacted surface, ρ is the avalanche flow density in kg m^{-3} and v is the avalanche velocity in m s^{-1}. A flow density of 300 kg m^{-3} is applied.

The total influence height on the ring net barrier is calculated according to:

$$d_{\text{tot}} = d + \frac{v^2}{2g\lambda} \quad (3)$$

in which d_{tot} is the total influence height in m, d is the original avalanche flow depth in m and $v^2/2g\lambda$ is the run-up height in m, where v is the avalanche velocity in m s^{-1}. λ is an empirical factor taking into account the loss of momentum during the impact and g is the acceleration of gravity. For light, dry snow avalanches λ is chosen to be 1.5 and for dense flow avalanches between 2 and 3 (Salm et al., 1990). For the back calculations we applied 2.5. The pressure is assumed to be constant over the flow depth d and from the top of the flow to the total influence height decreasing linearly to zero (Fig. 6). The back-calculated avalanche pressures are a lower bound because the calculation model did not consider the energy absorption of the ring net when the avalanche hits the barrier.

At post 4 of barrier A in February 2004 the wire rope clips with a failure load of 116 kN were broken. However the brake elements of the retaining ropes with a release force of 140 kN were not activated. The broken wire rope clip gives a lower and the non-activated brake ring an upper bound of the avalanche impact. The maximal avalanche pressure was estimated to be between 31 kN m^{-2} and 38 kN m^{-2} calculated with an avalanche speed of around 11 m s^{-1}, a flow depth of 0.5 m and a thickness of the snow pack of 1.5 m.

In winter 2006 weaker brake rings with a lower release force were installed. At the end of March a wet snow avalanche hit the section between post 1 and 2 of barrier A. Three brake rings of the retaining ropes were activated. The maximal tension force was 100 kN in the retaining rope, 140 kN at the upper anchor respectively. The maximal avalanche pressure was around 55 kN m^{-2} calculated with an avalanche speed of 13.5 m s^{-1}, a flow depth of 0.5 m and a thickness of the snow pack of 1.5 m. Using the avalanche dynamics program AVAL-1D (Christen et al., 2002), a quasi-one-dimensional, hydraulics-based and depth-averaged continuum model developed at the SLF, the avalanche from 2006 was back-calculated. The exact avalanche release area and the fracture depth were unknown and had to be estimated. We assumed a fracture depth of 0.5 m and a length of the starting zone of 113 m. For an unconfined flow with the friction parameters for wet snow avalanches μ=0.33 and ξ=1200 m s^{-2} (Christen et al., 2002) the velocity at the location of barrier A is 13.6 m s^{-1} (Fig. 7) and the flow depth is 0.44 m. These values are in good correlation with the results from the back-calculations with the static model.

4.2.2. Snow pressure

The theory of snow pressure calculations was mainly developed in regard to the design of snow supporting structures in the starting zone of avalanches. The resultant snow pressure in the line of slope S'_N per

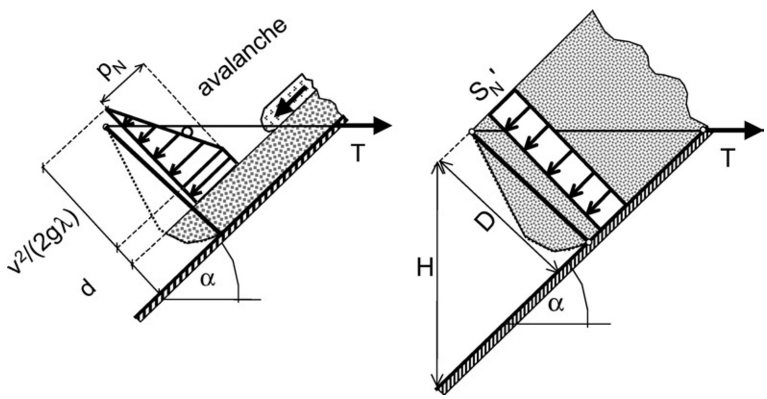

Fig. 6. Rockfall barrier with load distribution of avalanche impact (left) and snow pressure (right). The tension force T in the retaining cable is calculated by taking the moment about the hinge of the post.

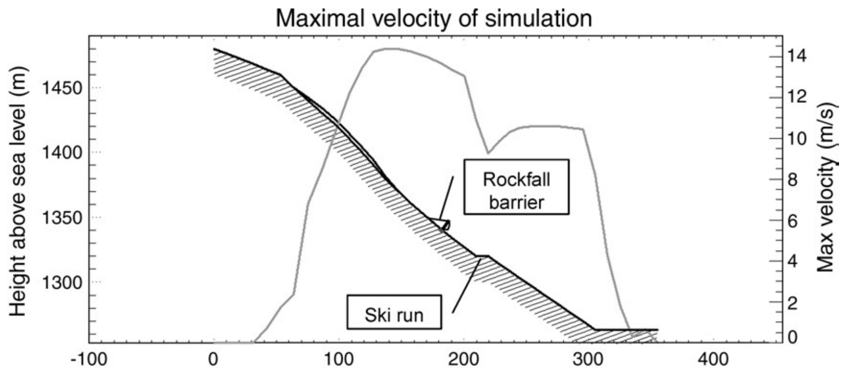

Fig. 7. Topography of the avalanche path at the study site in Fieberbrunn with AVAL-1D velocity profile of the avalanche at the end of March 2006. At the location of the rockfall barrier the avalanche speed is 13.5 m s^{-1}.

unit length across the slope on a rigid wall is formulated in the technical guideline for defense structures in avalanche starting zones (Margreth, 2007) as follows:

$$S'_N = \rho \cdot g \cdot \frac{H^2}{2} \cdot K \cdot N \left(\mathrm{kN\ m^{-1}}\right). \quad (4)$$

In Eq. (4), ρ is the average snow density (t m^{-3}), g is the acceleration due to gravity (m s^{-2}) and H is the vertical snow height (m). The gliding factor N was empirically classified in the technical guideline according to field-tests with respect to ground roughness and slope exposition. K is the creep factor which depends on the snow density ρ (t m^{-3}) and the slope angle α (°). The snow pressure is evenly distributed over the height of the snow pack (Fig. 6). We suppose that the reduction of the snow pressure by the flexibility of the net is compensated by the weight of the sack formed by the bulging ring net, which is not considered in the calculation.

We assume that the maximum snow pressure was in winter 2004 when at post 4 a mean snow height of 4.8 m and a snow density of 450 kg m^{-3} were measured. The brake elements of the retaining ropes with a release force of 140 kN were not activated. The maximal snow pressure was smaller than 88.5 kN m^{-1} whereas the creep factor K was 0.85 and the glide factor N was smaller than 2.0.

We think that the avalanche pressure in the four test winters was larger than the snow pressure and thus the determining factor for the loading. The snowpack behind the barrier consisted mainly of avalanche deposits. We suppose that creep and glide of an avalanche deposit is much reduced because of the low deformability compared to an undisturbed snow pack. However we believe that the weight of the filled ring net determines the vertical loading of the posts.

4.3. Structural behaviour

In winter 2004 brake rings of the lower support ropes were activated and wire rope clips that function as rated break points and fix the support ropes to the posts were broken. The loading of the lower support rope was higher compared to the upper support rope. Because of the broken wire rope clips the effective height of the barrier was reduced by 1.65 m and consequently the bulge of the completely filled ring net increased up to 2.5 m (Fig. 4). If the support ropes are properly fixed to the top and base of the posts the ring net is much tighter and therefore the bulge is smaller. Due to the loading of the barrier the post turns by 1° to 5° in upslope direction and the retaining rope is displaced downward. The overturn of the posts in upslope direction is not problematic.

The high vertical and transverse loads deformed the ground plates and anchors of the post foundation. The strength of the groundplate and the load transmission to the anchors was insufficient. The vertical loads due to snow pressure seem to be higher compared to rockfall. In winter 2005 a wire rope anchor of the lateral fixation of the upper support rope was pulled out. Due to the failed anchor the two outer posts were slanted by maximally 20°. However the stability of the whole barrier was not critical. In summer 2005 the two barriers were completely re-adjusted. All foundations were reinforced with a concrete base and the support ropes were directly fixed to the groundplate respectively to the post head without a rated break point. Winter 2006 demonstrated that the re-adjusted barriers withstood high avalanche and snow pressure loads without

Fig. 8. Rockfall barrier at site 1, Attersee, Austria, 17 March 2006. Photo by Geobrugg Austria.

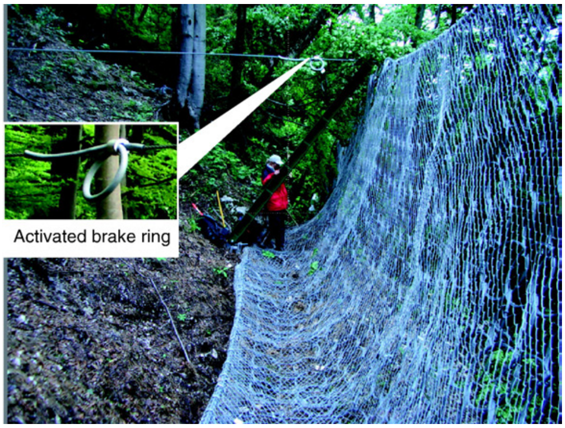

Fig. 9. Rockfall barrier at site 1, Attersee, Austria, 7 June 2006.

damages. Furthermore the deformation of the net was much smaller compared to winter 2004. The bulge of the completely filled net was 1.40 m and the sag of the upper support rope was maximally 0.55 m.

5. Results of case studies

Winter 2006 was very rich in snow in central and northern Austria. On the one side the new snow sums were very high and on the other side warming periods were missing. We investigated rockfall barriers in the area of Attersee which were hit by wet snow avalanches in February 2006.

5.1. Attersee, site 1

A rockfall barrier consisting of 7 posts is situated below a 40 m high cliff in a 200 m long and 60° inclined avalanche path. The 4 m high barrier Geobrugg RX-150 with a post spacing of 9 m was dimensioned on a rockfall impact energy of 1500 kJ. Four sections of the barrier were completely filled by two wet snow avalanches (Fig. 8). Most of the avalanching snow overtopped the barrier and caused damages to the barriers situated downslope. The later inspection of the snow free barrier showed that most of the brake rings in the retaining ropes responded between 35% and 65%, whereas two brake elements in the lower support ropes responded to a maximum of less than 5%. The maximum tension force in the upslope anchor was around 115 kN. The residual deflection of the ring net was maximally 2.2 m and was caused mainly because of broken rated break points (Fig. 9). Due to the high vertical loads in the posts some base plates were deformed and one anchor bar was broken.

Back-calculations resulted in an avalanche velocity of minimally 10 m s^{-1} with a flow depth of 0.3 m. The corresponding avalanche pressure was at least 30 kN m^{-2}. The main structural elements of the barrier such as ring nets or posts were not damaged and could be re-used for the repair.

5.2. Attersee, site 2

Two 9 m long sections of a 1500 kJ rockfall barrier were completely filled by a wet snow avalanche (Fig. 10). Only minor snow masses overtopped the 4 m high barrier Geobrugg RX-150. The small avalanche path has an inclination of 47° over a distance of 125 m. At the barrier site the slope inclination is 35°. The surface inclination of the banked-up snow was 33° measured over a distance of 11 m (Fig. 11). The mean height of the stopped snow behind the barrier was 3.6 m and the density was with 480 kg m^{-3} rather high. The catching capacity of the barrier was around 40 m^3 m^{-1}.

Fig. 10. Rockfall barrier at site 2, Attersee, Austria, 22 March 2006.

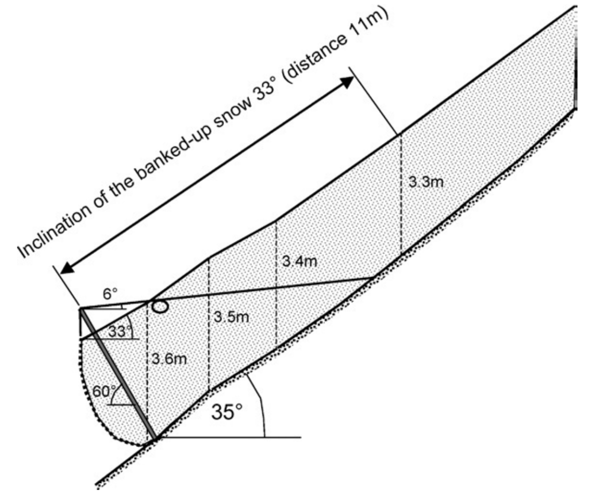

Fig. 11. Rockfall barrier at site 2, Attersee, Austria. Snow distribution on 22 March 2006.

The later inspection of the snow free barrier showed that the brake rings in the retaining ropes of three posts responded between 4% and 43% corresponding to a maximum tension force in the upslope anchor of around 60 kN. The brake elements in the support ropes did not respond. The maximal bulge of the ring net was 1.5 m. The avalanche impact was at least 22 kN m^{-2} with a velocity of minimally 8.5 m s^{-1} and a flow depth of 0.3 m. No repair work was necessary.

The observations of winter 2006 confirmed the experiences gained in the study site in Fieberbrunn. In several locations small wet snow avalanches with avalanche velocities smaller than 9 m s^{-1} were stopped by rockfall barriers with no or very small damages. In most of the studied barriers the determining loading was caused by avalanches and not snow pressure. The weakest point was the strength of the brake elements in the retaining ropes. In a few cases rockfall barriers collapsed mainly because of broken retaining ropes or failed upslope or lateral anchors. Damaged posts or ring nets were never observed.

6. Design procedure

Based on our findings a design procedure for an optimized application of rockfall barriers in areas exposed to avalanches and snow pressure was developed (Fig. 12). The main goal is to compare the rockfall load with the avalanche and snow pressure load and to choose the barrier type and dimensions respectively.

The procedure includes the following steps:

a) Preselection of rockfall barrier

The key parameters for the selection of a rockfall barrier type are the kinetic energy and the bounce height of a rockfall event (Spang and Krauter, 2001). The distribution along the slope profile of both parameters can be obtained with rockfall simulation.

b) Avalanche and snow pressure hazard evaluation

In a next step the avalanche and snow pressure hazard at the barrier location must be assessed. In the alps avalanches break loose typically on slopes steeper

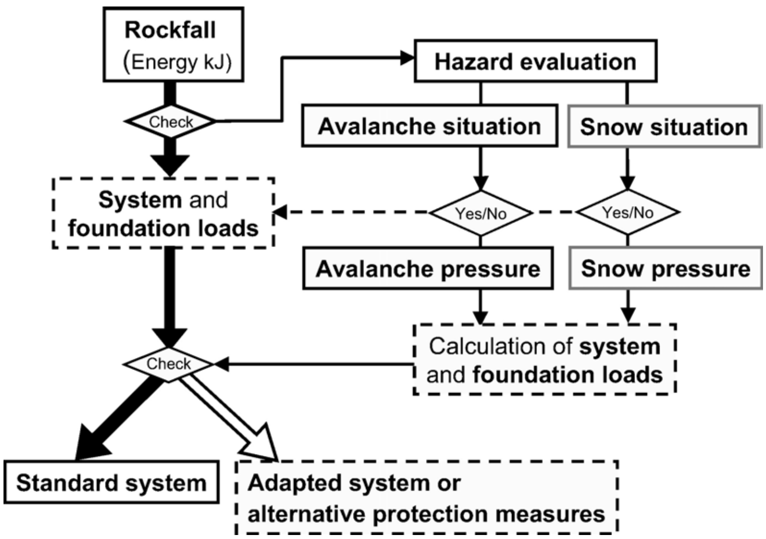

Fig. 12. Procedure for an optimized application of rockfall barriers in areas exposed to avalanches and snow pressure.

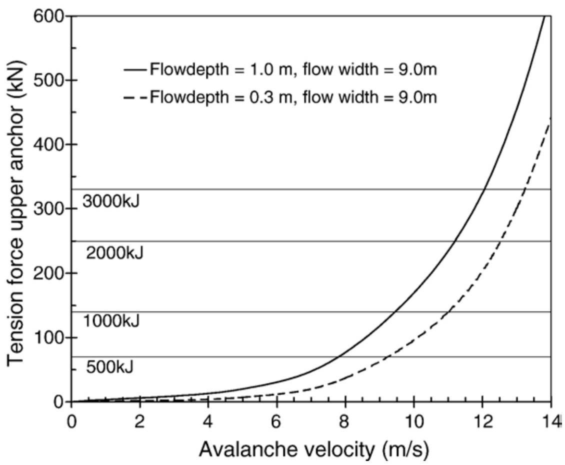

Fig. 13. Total tension force T at the upper anchor of a rockfall barrier (structure height 4 m, post spacing 9 m). Comparison of T induced by an avalanche impact (snow density 300 kg m^{-3}, snow height 1.0 m) with a rockfall impact (energy).

than 30° and at altitudes higher than about 500 m a.s.l. On slopes steeper than 40° they are much more frequent than on slopes less inclined than 35°. If the height difference from the upper end of the release area to the barrier location is less than about 15-20 m or if the angle between the upper end of the release area and the barrier location is smaller than 25° the avalanche hazard is negligible. Barrier locations in depressions with a confined avalanche flow and a low ground roughness are unfavourable. The information on former avalanche events are very valuable for the hazard assessment.

Snow pressure can generally be neglected if the extreme snow depth at the barrier location is smaller than 1.0 m or if the slope inclination is less than 25°. Smooth and even terrain with snow heights larger than about 2.5 m and inclinations between 35° and 45° is unfavourable. Snow pressure is much reduced if the barrier is located at the edge of a terrace.

c) Quantification of avalanche and snow pressure

The avalanche and snow pressure loads are quantified. For the calculation of the avalanche pressure the flow velocity, the snow density, the flow width and the flow depth have to be assessed at best with avalanche simulation models such as AVAL-1D (Christen et al., 2002). Especially the velocity and the flow width can cause high areal loads.

The snow pressure, which depends mainly on the snow depth and the glide factor, can be calculated according to the technical guideline for avalanche defense structures in the starting zone (Margreth, 2007).

d) Comparison of the system and foundation forces

The system and foundation forces of certified rockfall barriers are relatively well known. The forces are measured during the full scale certification test (Gerber et al., 2003). The reaction forces in the main structural elements due to avalanches and snow pressure can be estimated by replacing the dynamic with a static loading. The tension force in the retaining rope is calculated for avalanche and snow pressure loading and compared with the tension forces measured in the certification test for different barrier types (Fig. 13 and 14).

The comparison shows that the tension force at the upper anchor of a standard 1000 kJ barrier with a post spacing of 9.0 m and a structure height of 4.0 m is equalled if the avalanche velocity is around 8 m s^{-1} with a flow depth of 1.0 m or if the snow depth is 3.0 m with a glide factor N of 2.5 respectively.

e) Selection of rockfall barrier

The pre-selected barrier can be installed if avalanches and snow pressure cause smaller forces than rockfall. In areas with an abundant snow pack attention should be paid to the release point of the brake elements in the retaining ropes and to the foundations of the posts. If avalanches or snow pressure cause higher forces than rockfall the barrier system must be adapted. Stronger structural members, reduced post spacing, replacement of rated break points and foundations of the supports reinforced with a concrete base should be chosen.

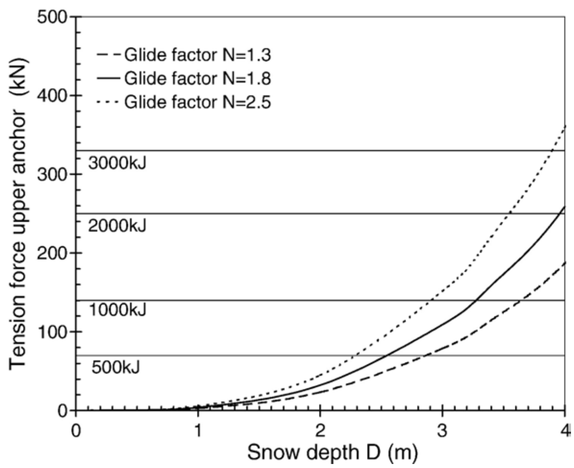

Fig. 14. Total tension force T at the upper anchor of a rockfall barrier (structure height 4 m, post spacing 9 m) in relation of snow depth D and glide factor N. Comparison of T induced by snow pressure (snow density 300 kg m^{-3}, slope inclination 40°) with rockfall impact (energy).

However if avalanches cause much higher forces on a barrier than rockfall alternate mitigation measures such as rockfilled dams may be necessary.

7. Conclusions

The interaction of flexible ring net rockfall barriers with avalanches and snow pressures was studied during four winters. Based on our findings a design procedure for an optimized application of rockfall barriers in areas exposed to avalanches and snow pressure was developed. The main goal is to compare the rockfall load with the avalanche and snow pressure and to choose the barrier type and dimensions respectively.

In several locations small wet snow avalanches were stopped successfully. However the main problem turned out to be the insufficient retention capacity during the whole winter and the structural behaviour. If rockfall barriers are applied to stop small avalanches then the structure height should be determined on the base of a mass balance analysis between potential starting zone and catching capacity. At the study site in Fieberbrunn the maximal catching capacity was 38 m^3 m^{-1}.

Most of the damages to the barriers investigated in our studies were caused by avalanches. The weakest points were found to be the retaining ropes and the post foundations. If impact forces due to avalanches and snow pressure exceed those of rockfall the system must be adapted. For an appropriate reinforcement the main input factors determining snow pressure (snow height, glide factor) and avalanche pressure (velocity, density, flow depth) have to be assessed. The most important points in regard of the interaction of avalanches and snow pressure with a ring net barrier in comparison to rockfall are:

– Stronger brake rings should be used especially for the retaining ropes.
– It is favourable to install the retaining ropes in the direction of the slope.
– The support ropes should be fixed directly to the posts without rated break points.
– Brake rings in the support ropes within the sections are not necessary.
– Micropile and anchor foundations should be reinforced with a concrete base.
– If no concrete base can be applied, a larger base plate has to be considered.
– A smaller spacing of posts should be applied.

The back-calculations in this paper were made with a simple static model. This approach is dissatisfying especially for an avalanche impact on a highly flexible ring net. More research has to be done on this subject. It is planned to simulate the behaviour of flexible barriers under the dynamic areal loads of avalanches with the simulation program FARO (Volkwein, 2005), originally developed to simulate rockfall impacts. As a result we expect a more precise information on the internal forces of the barrier which allows to design the structural members more precisely. A further point is that the prediction of the main input parameters describing snow pressure and avalanche impact is still difficult and requires experience.

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