

ALPS2.0: INTERACTION OF FLEXIBLE ROCKFALL BARRIERS WITH STATIC AND DYNAMIC SNOW PRESSURE

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ABSTRACT: Due to the demand for protection systems with a design on the combined load case rockfall and snow pressure, a research project is enrolled for the better understanding of the load distribution in rockfall barriers which are exposed to snow load. Static snowpack forces and dynamic snow slide pressures act over a much larger area and over longer time periods, compared to dynamic rockfall events. Since rockfall barriers are not primarily designed for the former load case, they often must be adapted if a certain snow load is expected. To obtain a first semi-quantitative understanding of the interaction and performance of rockfall barriers with snow pressure and snow slides, a case study has been performed from 2003-2006 in Fieberbrunn, Austria. This resulted in a first design concept, which is still widely used today (Margreth & Roth, 2008). The aim of the measurement campaign in the winter 2023/24 is to verify the findings of the first project, to apply those for different types of rockfall barriers and to determine a fully quantitative load distribution for a given snow load. Four barriers in the Swiss and Austrian Alps are equipped by cameras and load cells to ensure a real-time monitoring of all barriers at any time. For the determination of the load distribution, the behaviour of the individual components such as brakes, posts, ropes, net and anchors are studied. The broad objective is to identify at which snow load adjustments in the individual systems are necessary and which precautions must be taken at best from this point on.

KEYWORDS: Snow pressure, avalanche dynamics, avalanche and rockfall protection

1. INTRODUCTION

For around 30 years, rockfall barriers have been subjected to extensive full-scale tests to study their interaction with impacts (Baumann, 2018). Using flexible ring nets and braking elements, these barriers have been optimized to absorb high punctual impact energies of up to 10,000 kJ (Geobru gg, 2024). These barriers reliably protect vulnerable infrastructures such as transportation networks, energy supplies and settlements. In mountainous regions, flexible rockfall nets are exposed to avalanches and snow pressure. The interaction of flexible rockfall barriers with snowpack differs significantly from the interaction with rockfall. While the rockfall nets are adapted to high punctual impact energies, snow loads have a permanent and extensive effect on the barrier. If the rockfall barriers are not designed to withstand these loads, they can be damaged during the winter.

In 2003-2006, a semi-quantitative study was carried out to determine the snow loads and to optimize the systems so that they can absorb static snow pressure loads without damage. The tests have confirmed that rockfall barriers are generally capable of stopping snow slides. The reaction of the barriers to the local snow loads in terms of net deflection and damage was investigated at several locations, such as Fieberbrunn, Austria, see Fig. 1. This resulted in a first design concept, which is still widely used today. The scheme is shown in Fig. 2. However, the loads were not

measured but reconstructed based on the damage patterns. The retaining ropes, the rope connections and the post foundations were identified as relevant sections. The outstanding role of the brake rings in absorbing the surface loads was also emphasized (Margreth & Roth, 2008). Expanding on the results of this study, a measurement campaign was initiated in 2023, whereby a real-time remote measurement campaign and a fully quantitative measurement approach using load cells and camera monitoring techniques was aimed for.



Figure 1: Rockfall barrier in Fieberbrunn, Austria, on April 15, 2004 (Margreth & Roth, 2008)

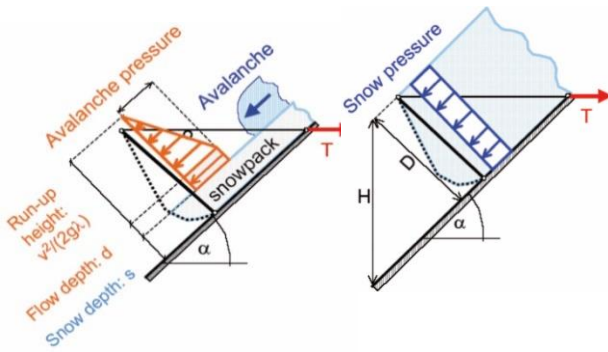


Fig. 2: Design concept of rockfall barrier with load distribution of avalanche impact (left) and snow pressure (right). The tension force T in the retaining rope is calculated by taking the moment at the hinge of the post. (Margreth & Roth, 2008)

2. TEST SITES IN THE ALPS

In the current monitoring project, four test sites are spread over the Swiss and Austrian Alps to identify possible regional differences and to better intercept local meteorological events regarding snow conditions. The local conditions essentially depend on the typical cloud accumulation due to low pressure areas in the northwest (Atlantic Ocean) and south (Mediterranean Sea) and the associated precipitation exposure on site (Zappa et al., 2012).

The benchmark for the planned barrier equipment is the existing rockfall barrier built at the Chant Sura test site located at Flüelapass, Canton Grisons, Switzerland. Full scale in-situ rockfall experiments were performed between 2018 and 2021 within the framework of a research collaboration between Geobruigg AG and the WSL Institute for Snow and Avalanche Research (SLF), located in Davos, Canton Grisons, Switzerland. The tests were performed with instrumental blocks to quantify how blocks decelerate at barrier impact in real conditions. In addition, data was obtained for the calibration of trajectories and rock-soil interaction (Caviezel, A. et al., 2022). GUARDs and load cells were mounted on the various supporting steel ropes to determine the tension force and measuring bolts were installed on the posts to determine the post forces. After the test series, a camera was installed on a middle field post in the visual axis of the barrier to ensure permanent remote monitoring of the barrier also during the winter, as shown in Figure 3. The other three barriers to be chosen for the measurement campaign are in regular operation. The barriers are at Felbertauern, East Tyrol, Austria (Fig. 5); Rosalba, Canton Ticino, Switzerland (Fig. 6) and Arolla, Canton Valais, Switzerland (Fig. 7).



Fig. 3: Snow filled rockfall barrier at Chant Sura in January 2021.

Generally, low construction heights from 3 to 5 m were chosen to increase the probability of full snow filling. Apart from Arolla, all barriers have a straight barrier line with a maximum of 6 fields. For the evaluation and modeling, uniform slopes with inclinations between 30° and 40° are preferred on the mountain side. Although the sites differ in terms of geology and soil roughness, the geometric requirements are met at all sites. Full filling and snow slides have been documented several times over the last 10 years at all barriers. At Felbertauern, the net has already had to be replaced due to a snow slide, and at Rosalba, posts and ropes have already been replaced several times. In Rosalba, anchored logs were laid along the contour lines on the mountain-side of the barrier to mitigate snow slide activity and further damage.



Fig. 4: Rockfall barrier at Chant Sura on June 13, 2023.



Fig. 5: Rockfall barrier at Felbertauern on July 4, 2023.



Fig. 6: Rockfall barrier at Rosalba on September 8, 2023.



Fig. 7: Rockfall barrier at Arolla on June 15, 2023.

3. METHODOLOGY

Before device installation, all barriers are measured in summer 2023 for post spacing, barrier height, rope inclination post inclination, initial net deflection, initial brake activity, slope inclination and sliding factor of the terrain according to the SLF guideline (FOEN, 2007). The barriers are also assessed for further signs of minor damage.

To gain a fully quantitative understanding of the load distribution, Geobruigg rockfall barriers in snow intensive locations are equipped with load sensors of the 7th GUARD generation (Geobruigg, 2024). Per barrier, 6 GUARDs are mounted on the upper support rope (1/6) the lower support rope (2/6) and the retaining ropes (3/6). The GUARDs transmit the measured rope forces to a platform every two weeks. As soon as an acceleration is triggered, e.g. due to rockfall or snow slide, the measurement results are transmitted immediately to the platform providing a real-time remote monitoring of the barrier. The measuring instruments on the lower support ropes are also protected from the snowpack with protective housings made of steel. A solar-powered camera, offering a side view on the barrier, is placed on the head of the border post to monitor the entire barrier, like on the site at Chant Sura. The image data from the camera is immediately transmitted and stored online, so that real-time monitoring of all barriers is possible at any time. For redundancy, a wildlife camera suitable for the weather conditions is installed on another post and provides a second perspective on the situation. The

image data from this camera is transferred to a SD card and can be analyzed after the winter. To evaluate the snow height from the image data, the first post in the cone of light is provided with luminous paint. The snow height measurements are supported by an image measurement software, which allows remote evaluation and can be used to quantify the maximum net deflection. During a snowy winter with pronounced snow depth and snow slide activity, in-situ snow density measurements are performed by the snow water equivalent probe (WSL, 2020). In addition, the net deflection, post inclination and volume of the snowpack are investigated at this time via drone-supported photogrammetric evaluation and compared to the status in summer. The aim of the field measurement is to achieve a precise point-by-point quantification of the snow loads at this decisive point in time.

The weather conditions in high alpine locations over the winter can be very challenging for the force measuring instruments. To validate the measured tension forces, the results of the GUARDs are confirmed in Chant Sura by mounting load cells ("MicroStrains") combined with a 3-channel wireless sensor to the same ropes during the same period, see Figure 8. The rope forces are measured three times per day and the results are transmitted online. Besides to the rope forces, side bracing forces and post forces at post 5 and 7 are measured.



Fig. 8: Rockfall barrier at Chant Sura. Retaining ropes equipped with GUARDs (yellow) and "MicroStrains" (purple).

4. RESULTS

4.1 Winter conditions 2023/24

The snow conditions varied greatly depending on the location. In Felbertauern, a below-average amount of snow was recorded, while in Arolla a snow depth of just over 1m was measured in March 2024, which corresponds to the long-term average in the region (SLF, 2024a). Minimum one snow slide with a thickness of almost 2 m and a width of 8 m was recorded in fields 6 and 7, as

shown in Fig. 9. The mean snow density over the snow profile in field 6 was 320 kg/m^3 .



Fig. 9: Rockfall barrier at Arolla on March 7, 2024 with recorded snow slide in field 6 and 7.

During the winter of 2023/2024, above-average snow depths were recorded in the region of Chant Sura (SLF, 2024b) and Rosalba (SLF, 2024c). In the beginning of April, the snow height in Chant Sura was approximately 2.50 m, leading to a half-filling of the barrier (see Fig. 10). The flexible interaction between load bearing and reaction in the form of net and rope sag is clearly visible. The mean snow density over the snow profile in field 1 was 370 kg/m^3 .

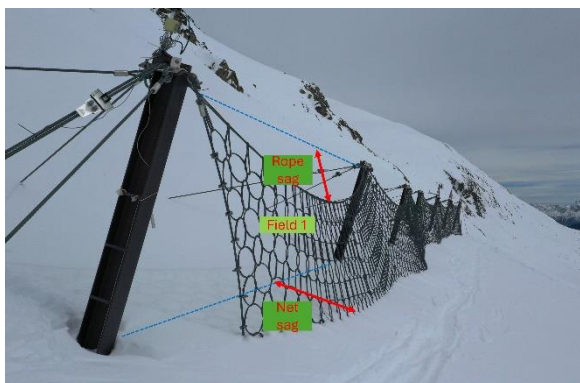


Fig. 10: Rockfall barrier at Chant Sura on April 4, 2024 with recorded rope and net sag in field 1.

In Rosalba, the barrier was completely filled by snow in April 2024, as shown in Fig. 11. The snow cover even overtopped post 1 by 1.60 m. This corresponds to a punctual perpendicular snow depth of almost 6 m. Furthermore, this location is highly exposed to snow slides; several snow slides were recorded by the GUARD sensors (see Chapter 6 *Results*). The mean snow density over the snow profile in field 1 was 410 kg/m^3 .

The coldest temperature recorded by the GUARD was -18°C , measured on January 20, 2024 in Chant Sura. The different snow and weather conditions over the winter and at the different locations allow a broad comparison in the recorded snow loads and conductivity of the GUARD.

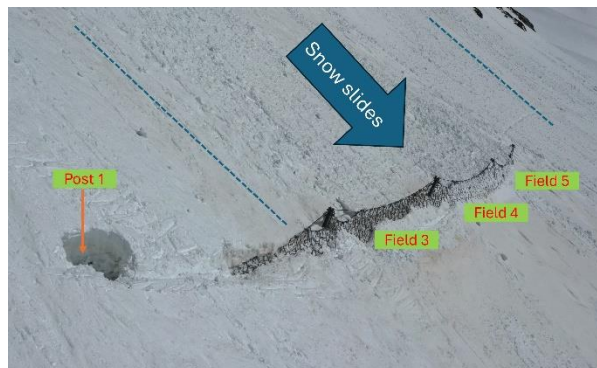


Fig. 11: Rockfall barrier at Rosalba on April 11, 2024 with overtopped post 1 and recorded snow slides in fields 3 to 5.

4.2 Snow slides and avalanches

As soon as the acceleration sensor detects activities, triggered for example by snow slides, rock-falls or static overload, an immediate digital transmission is triggered. Only activities that can be clearly or with the highest probability attributed to snow slides are studied.

No snow slides were detected at the Felbertauern site in winter 2023/2024 due to the poor local snow conditions. In Arolla, smaller accelerations of the suspension cables of up to 10g were detected, but they could not be unequivocally attributed to snow slides. The inspection on March 7 revealed a landslide wedge between fields 6 and 7 with a catchment area in the rock face above the barrier, see Figure 9.

In Chant Sura in December 2023 and January 2024, several smaller accelerations of up to 10g were recorded in the upslope anchor rope in field 2 and in the upper suspension rope field 1. These occurred following a period of heavy precipitation, which produced almost 1.5m of fresh snow within 2 weeks.

These could be clearly classified as snow slides as they were recorded on the camera, see Figure 12 and 13. No further events could clearly be linked to snow slides at the barrier after the end of January 2024.



Fig. 12: Recorded snow slide on field 1 on December 19, 2023, at Chant Sura by the real-time monitoring camera "Reolink".

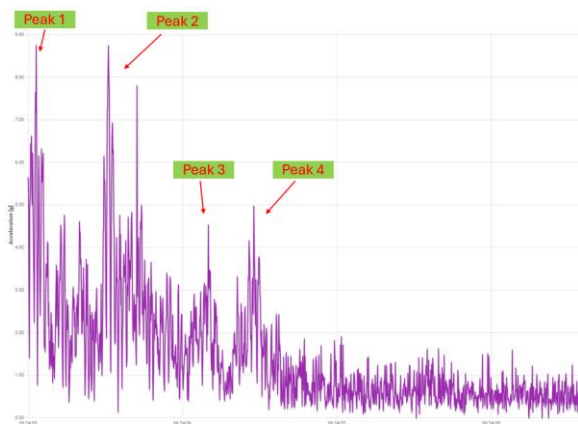


Fig. 13: Corresponding response spectrum of the GUARD's accelerometer at the top support rope to the snow slide on December 19, 2023, in Chant Sura with two main peaks with 9g at the beginning with the main slide, followed by two smaller snow slides around 5g (peaks 3 and 4).

Due to the high snow amount, but also due to the soil conditions, south exposure and slope inclination, significantly more snow slides were recorded at Rosalba, with a focus on spring 2024. The barrier has already been damaged by high snow loads and snow slides in previous years. The last refurbishment was carried out after the winter of 2019/2020 and anchored logs were installed above the barrier to increase ground friction with the aim of minimizing static and dynamic snow pressure on the barrier.

The events after the field inspection in April 2024 were proven beyond doubt to be snow slides. During the field inspection itself, 5 major snow slides were documented, which overflowed the barrier, as the snow depth had already reached the barrier height (see Figure 11). On May 1, a rope acceleration of approximately 26g was measured at the upslope anchor rope on field 2,

see Figure 14. By restraining the rope in the high snow cover, the oscillation of the rope is immediately prevented, in comparison to Figure 13, with the rope half-restrained.

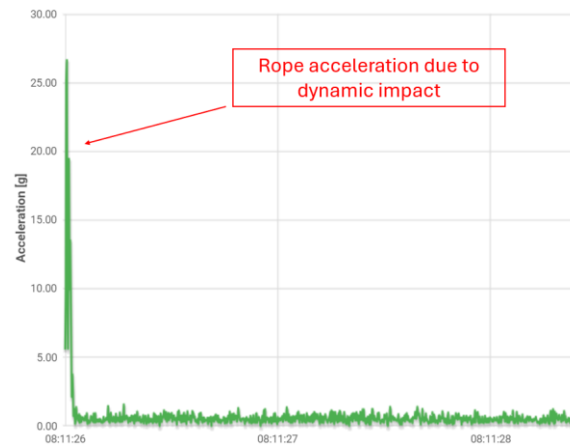


Fig. 14: Response spectrum of the GUARD's accelerometer to the snow slide on May 1, 2024, in Rosalba. The short oscillation time can be explained by the extreme snow height provoking a dampening.

In addition, controlled blasting was triggered by the cantonal road authority above the barrier on June 11 to be able to open the pass road a few days later. A total of four blasts were carried out. All the avalanches triggered by the blasting triggered an acceleration in the ropes of the rockfall barrier and thus a GUARD notification. The explosions were documented on video by the cantonal road authority of Ticino, see Figure 15. A resulting maximum acceleration of 155 g was measured on the upslope anchor rope on field 4 during the resulting avalanche impact, see Figure 16.



Fig. 15: Documented avalanche impact on the rockfall barrier on June 11, 2024, in Rosalba with highlighted GUARD mounted on the upslope anchor rope.



Fig. 16: Corresponding response spectrum of the GUARD's accelerometer to the avalanche impact on June 11, 2024, in Rosalba.



Fig. 17: Broken top support rope at rock connection on July 15, 2024, in Rosalba.

4.3 *Summer inspection 2024*

No summer inspection was carried out in Felbertauern as no significant load case was documented over the winter 2023/24. No major damage was found at Arolla and Chant Sura after the winter of 2023/24. At most, the retaining ropes would have to be tightened here. The barrier in Rosalba was exposed to an overload case and was therefore examined in detail in July 2024. It was found that the upper suspension rope at the rock connection had broken, see Figure 17. The ropes were also partially running, probably due to insufficiently tightened wire rope clips. In addition, the anchor head of the upper suspension rope was bent. The spiral rope anchors of the retaining ropes were exposed by 10-70 cm depending on their position due to the high snow pressure load. In addition, most of the anchored logs above the barrier failed due to the high snow load; one anchored log failed completely and was transported into the barrier. It can be assumed that the snow pressure load on the barrier has also increased due to the failed anchored logs. It is interesting to note that the rings close to the upper suspension ropes remained in the plastic range, contrarily to those close to the lower suspension rope, as shown in Figure 18. Together with the damage pattern of the upper suspension ropes, this suggests that the snow forces were maximum at the height of the upper suspension rope and lower down into the elastic range. For the next winter, it is recommended to replace the damaged ropes and brakes at the rock connection, to re-tension the suspension ropes, to reposition the running cables and to reinforce the uphill anchorages with concrete foundations, see Figure 19. All in all, it appears that the barrier overcame the winter quite well despite the overload case and is fully operational again after the refurbishment.



Fig. 18: Plastically deformed ring net close to top support rope on July 15, 2024, in Rosalba.



Fig. 19: Proposed uphill concrete anchorage solution for Rosalba.

5. DISCUSSION

In the winter of 2023/2024, snow conditions at the investigated locations were very good in some cases compared to previous winters. The local distribution of the sites across the Alps with different local weather phenomena showed complete success. The full filling of the barriers with snow varied from non-existent (Felbertauern) to 1/3 filling (Arolla) and 2/3 filling (Chant Sura) to overfilling (Rosalba). In addition, multiple snow slides were observed and documented by GUARDs, particularly at the snow-rich locations. In another winter season, the snow conditions could look completely different at each site.

This was the first time ever that the GUARDs were used in such a measurement campaign under such adverse climatic conditions, and as a key component in combination with other measurement equipment. All in all, the results of the data transmission are satisfactory.

It was found that the rope forces in the upper suspension rope are in some cases significantly greater than in the bottom suspension rope. This can also be seen qualitatively in the torn upper suspension rope in Rosalba. First results from Chant Sura confirm these findings. The decisive load on the upper suspension rope is derived from the net sag due to snow filling. In addition, the forces in the bottom suspension rope are reduced by soil friction. At Chant Sura, the retention ropes show similar tension forces as the bottom suspension rope. These findings need to be validated in further investigations and research.

A significant overload case was detected at the Rosalba site. The barrier was exposed to high static snow pressure and multiple snow slides as well as overflows over the winter, especially during the spring season. In addition, the barrier was exposed to avalanches in June due to controlled blasting. In view of the forces involved, it suffered only minor damage and is fully operational again after a minor refurbishment.

This confirms the reliability of the flexible rockfall systems manufactured by GeobruGG AG.

6. OUTLOOK

In the winter 2023/2024, the data basis and measurement experience for determining the load transfer on rockfall barriers due to static and dynamic snow pressure were developed.

The aim of the study is to quantify the rope forces and, if necessary, post forces for the load transfer. To this end, the data obtained has now to be read out and the measurement results of the

GUARDs compared with those of the MicroStrains at the site of Chant Sura.

Due to the large number of snow slide events documented by the GUARD, the aim is also to develop a deeper understanding of the GUARD signals during snow slides. Parameters such as signal amplitude, duration of the oscillation or period may allow conclusions to be drawn in the future about how to distinguish snow slides from other impacts. If sufficient data is available, the use of artificial intelligence methods could be useful under certain circumstances. In this context, in the winter of 2024/2025 it is intended to lay sliding snow sheets on the uphill side of a field of the Chant Sura barrier in order to promote snow slides and collect more data about their behavior and the response spectrum of the GUARDs. These snow sheets consist of geotextiles and are developed by the University of Applied Sciences of the Canton of Grisons (Glover et al., 2021).

An important input parameter for determining the loads is the snow depth. This and the snow volume were recorded at all locations using drone measurements and should be studied in conjunction with point cloud formation. Furthermore, with this data basis, net deflections and post inclinations can be compared between summer and winter conditions.

There is unique video material of controlled avalanche blasting in the barrier in Rosalba. Here, the forces on the barrier could be determined in order to be able to draw conclusions about the load-bearing capacity of the barrier under dynamic snow impact.

Specifically, refurbishment of damaged individual parts of Rosalba must be carried out in the snow-free period 2024 due to the overload event that occurred.

In addition, damaged measuring equipment such as cameras need to be replaced, as some of them have been damaged by snow slides.

The overarching goal for the upcoming research work is to establish a consensus and a standard on how flexible rockfall barriers should be dimensioned under snow load by linking external parameters such as topographical and climatic site factors and internal parameters such as barrier geometry and material selection.

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