DESIGN OF FLEXIBLE ROCKFALL BARRIERS UNDER STATIC AND DYNAMIC AREAL LOADING FROM SNOW

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ABSTRACT: Flexible rockfall barriers are primarily designed to absorb high-energy point impacts caused by falling rocks. However, when installed in mountainous environments, they are exposed to a range of additional hazards that result in different loading conditions. Therefore, gravitational mass movements other than rockfall must be considered during the planning and design of such systems. The most critical dynamic loads arise from shallow landslides and avalanches. In addition, at higher altitudes and latitudes, static snow loading must also be considered.

In contrast to rockfall impacts, these loads act over an area rather than at a single point, representing a fundamentally different loading scenario for which the systems are not originally designed. If these real loading conditions are not adequately considered, they may lead to damage of individual components or, in the worst case, complete failure of the barrier.

The objective of this study was to develop a calculation method for flexible rockfall barriers that are subjected to static and dynamic areal loading. To achieve this, field measurements of static and dynamic snow loads on existing barriers were conducted. These data, combined with the mechanical properties of ring nets, the fundamentals of rope statics, and principles of snow and avalanche mechanics, form the basis for modelling areal loading scenarios on flexible structures. During field measurements, key parameters, including barrier deformation and the loading of individual components under static and dynamic areal loads, were recorded to calibrate and validate the developed calculation method.

By validating the system behaviour of rockfall barriers under snow areal loading, this calculation method can also be extended to other types of areal loading, for example, for the analysis of shallow landslide events. The final calculation approach integrates Excel-based workflows with structural analysis in RSTAB and is fully parametric, enabling efficient adaptation to a wide range of environmental and loading conditions in practical applications.

KEYWORDS: flexible rockfall barriers, snow loads, avalanche loads, rope statics, structural analysis, multi-hazard protection

1. INTRODUCTION

The present study is the result of a master's thesis conducted in the field of civil engineering at HTWG Konstanz – University of Applied Sciences, in collaboration with Geobrugg AG.

Rockfalls and snow avalanches are natural gravitational hazards that predominantly occur in alpine regions. One possible technical mitigation measure against rockfall is the use of flexible rockfall barriers, which are designed to catch falling rocks. These systems are subjected to high-energy, dynamic point loads. In contrast, avalanche protection structures are intended to prevent avalanches from releasing in advance and are therefore exposed to large-area, static snow loads.

When flexible rockfall barriers are installed in alpine environments, they are also exposed to snow pressure and snow slides for which they were not primarily designed. If this type of loading is not taken into account during the design phase, it may lead to damage of individual components or, in the worst case, complete failure of the barrier.

Since the structural behaviour of flexible rockfall barriers is highly deformation-dependent, it is particularly challenging to incorporate snow loading scenarios into standard design calculations. To address this issue, two research projects were conducted in 2003-2006 and 2023-24, during which several barriers were exposed to snow

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https://doi.org/10.15788/1790098890

loads (Margreth and Roth, 2007; Marc et al., 2024). The findings from these studies contributed to the development and verification of the calculation method described in this work.

2. AIM OF THE STUDY

To date, only rudimentary methods have been used to model the structural behaviour of flexible barriers under snow loads.

The aim of this study was to develop a calculation method for flexible rockfall barriers produced by Geobrugg AG under snow and avalanche loads. The method is intended to realistically capture the complex structural behaviour resulting from the interaction of steel nets, support ropes, steel posts, brake elements, and anchor ropes.

The approach was designed to be fully parametric, allowing for the consideration of varying terrain conditions, snow loads, barrier heights, and post spacing. It enables the determination of internal forces within the individual components, forming the basis for structural design and verification.

3. SNOW AND AVALANCHE LOAD

For the calculation procedure, load models for static snow pressure and avalanche impact had to be defined first.

For static snow pressure on sloped terrain, the method described in the Swiss guideline Lawinenverbau im Anbruchgebiet was adopted (Margreth, 2007). This approach is based on Haefeli's snow pressure theory, in which slope-parallel and slope-perpendicular pressures act uniformly over the snow depth on the obstacle (Haefeli, 1939).

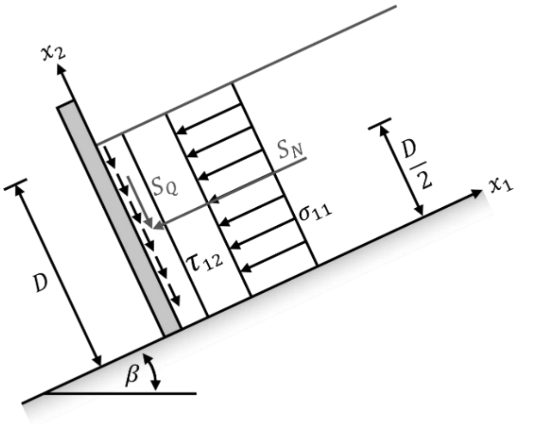

Figure 1: Creep pressure according to Haefeli.

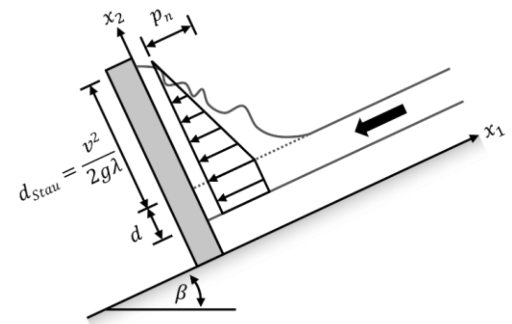

Figure 2: Avalanche pressure distribution on an obstacle.

For avalanche impact loading, the method by Voellmy and Salm was selected (Voellmy, 1955; Salm et al., 1990). In this approach, the avalanche pressure is assumed to be constant over the flow height and to decrease linearly with run-up height.

The calculation assumes that the avalanche impacts a rigid obstacle. However, when the flow hits a net structure, such as those used in flexible rockfall barriers, the actual pressure can be significantly reduced due to the net's permeability. To date, no reliable reduction factor is available. The described approach can therefore be regarded as a conservative upper bound for avalanche loading.

4. DEVELOPMENT OF THE CALCULATION METHOD

The calculation method is divided into two main parts. First, the snow load calculation, net analysis, and support rope analysis are carried out parametrically in Excel. Through an import function, the system geometry and the support rope forces, which were calculated in Excel, can be automatically transferred to the structural analysis software RSTAB.

In RSTAB, the remaining structural components, namely the posts and anchoring ropes, are analysed. In this method, the internal forces are passed sequentially from one structural component to the next, ensuring clear traceability and transparency of the results.

To improve the understanding of the following section, a system drawing of a typical rockfall barrier by Geobrugg AG is provided below:

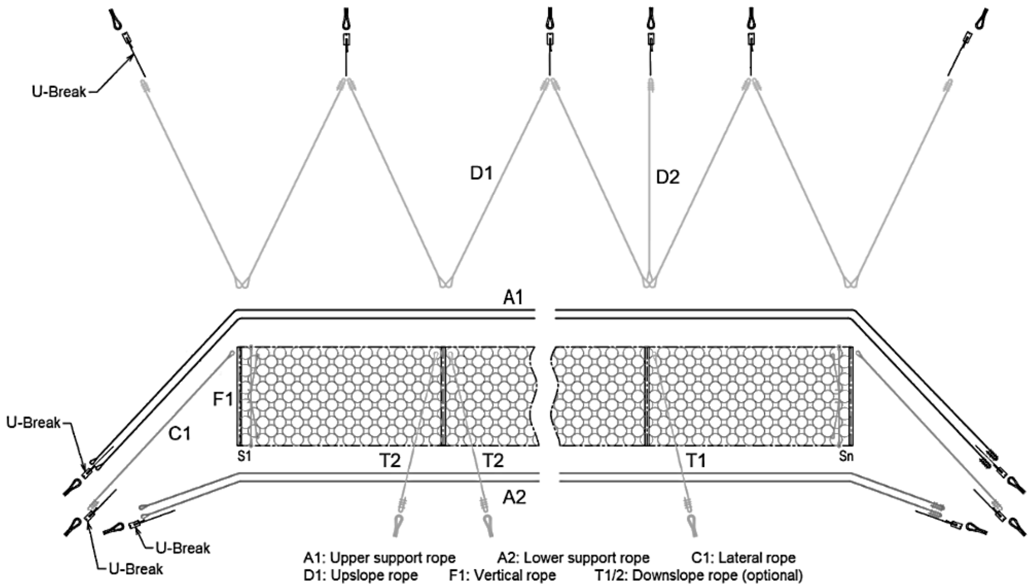

Figure 3: System drawing of a rockfall barrier from Geobrugg AG.

4.1. Snow and avalanche load calculation

The snow and avalanche loads can be specified in advance based on existing design criteria or external input, or calculated using the methods described above, considering site-specific factors such as slope angle, snow depth, and avalanche characteristics.

4.2. Net calculation

To improve transparency and simplify the calculation model, the individual components of the barrier are analysed step by step, with the resulting forces passed on to the subsequent elements. The process begins with the net, which is subjected to snow loading and is suspended between an upper and a lower support rope.

The aim is to determine the resulting net shape and the forces transmitted from the net to the support ropes. It is conservatively assumed that the entire snow pressure is transferred to the net, as snow cones are expected to form behind each mesh opening, enabling full load transfer despite the net's open structure. A planar load-bearing behaviour is assumed, allowing the net to be idealised as vertical strips behaving like single ropes suspended between supports.

Based on this assumption, the net can be analysed using basic rope theory. This requires information on the load distribution, the initial net height, the material's elongation behaviour, and the positions of the supports. The calculations are carried out parametrically in Excel. An iterative solution to the rope equations allows determination of the net shape, the resulting forces, and their directions. In the final step, the support reactions are calculated, which then serve as input for the calculation of the support ropes.

4.3. Support rope calculation

The upper and lower support ropes run continuously from the beginning to the end of the barrier and are deflected only at the tops and bottoms of the posts. Since the same snow load is assumed in every span, a rope segment between two posts can be analysed separately and modelled as a sagging single rope.

The post tops and bases act as support points. The load is taken from the previous net calculation and applied as a constant distributed load along the rope. The calculation is performed in Excel using the same iterative rope-theory approach as for the net.

4.4. Transfer of geometry and loads to RSTAB

RSTAB offers the possibility to import and export input data such as nodes, members, materials, and loads via Excel tables. To ensure that RSTAB correctly interprets the data, a predefined table structure must be followed. Each table contains structured information that defines the geometry and loading of the structural model.

The required table templates are integrated into the Excel tool. Parameters such as the selected system, slope inclination, the orientation of the support ropes, and the resulting forces acting on the posts influence the entries in these tables. To maintain a fully parameterised workflow, all table entries are generated dynamically using Excel formulas.

By importing the generated tables into a blank RSTAB model, the system is automatically created with the correct geometry, materials, number of spans, and load conditions. The sagging support ropes are modelled as non-structural members for visualisation purposes, while the lateral and upslope anchor ropes are modelled as straight tension members. All posts and ropes are modelled with pinned supports. Rigid links are used at the top of the posts to account for eccentricities in the rope connections.

The following figure shows an example of a generated system in RSTAB:

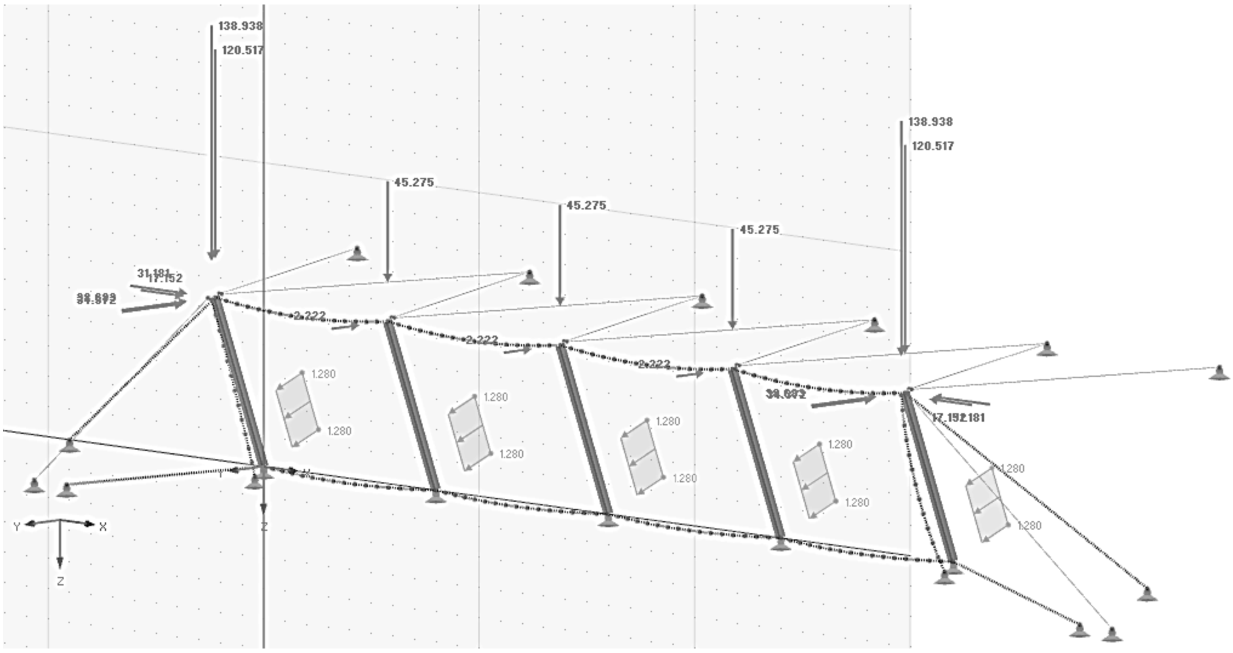

Figure 4: Generated system in RSTAB.

4.5. Calculation of posts and anchor ropes

The internal forces for the posts and anchor ropes are then determined in RSTAB. Since the structure is a rope-supported system, the analysis is performed according to third-order theory. The posts are primarily subjected to compression but also experience bending moments due to eccentricities at the post head and the explicit snow load perpendicular to the post. The lateral and uphill anchor ropes are subjected to pure tensile forces. The forces in the net and in the upper and lower main ropes have already been calculated in the Excel tool, as previously described.

5. RESULTS AND DISCUSSION

The objective of this study was to develop a calculation procedure for Geobrugg rockfall barriers exposed to static snow and avalanche loads. The calculations are performed in Excel and RSTAB and are fully parameterised. After entering the system parameters and site-specific factors, the expected snow load can either be calculated using the described approaches or specified directly. Due to the fully parametric setup, the internal forces of the individual components can be determined with minimal effort, and the subsequent structural design of the system components can also be performed.

To validate the developed calculation procedure, measured rope forces from the previous field tests were compared with calculated values. The results showed very good agreement, except for the forces in the lower support rope. In this case, the calculated forces were significantly higher than the measured ones. A plausible explanation for this discrepancy could be friction between the lower support rope and the ground, which was not accounted for in the calculation. However, this deviation results in conservative estimates, which is favourable from a safety perspective.

An important outcome of the study is that the developed methodology is not limited to snow- and avalanche-related loading scenarios. Since the calculation procedure is based on the parameterised transfer of distributed loads through the net, support ropes, posts, and anchor system, it can also be adapted to other natural hazard processes that generate comparable impact mechanisms. In particular, shallow landslides and debris-rich slope failures may be represented through appropriate load models, allowing the structural response of flexible barrier systems to be assessed using the same calculation framework. This demonstrates the broader applicability of the approach and supports the ongoing development of multi-hazard protection concepts for flexible barrier systems.

6. CONCLUSIONS

The developed calculation procedure provides an efficient tool for assessing the structural response of flexible rockfall barriers under static snow and avalanche loads. The strong agreement with field measurements confirms the validity of the approach, while its parametric structure ensures adaptability across various system configurations and site conditions.

Beyond its original application to snow-related hazards, the methodology also provides a framework that can be extended to other distributed dynamic loading scenarios. Processes such as shallow landslides or debris-rich mass movements may be incorporated through suitable load formulations, enabling the assessment of flexible barrier systems within a broader multi-hazard context. This versatility increases the potential value of the methodology for future infrastructure protection and natural hazard risk mitigation in alpine environments.

ACKNOWLEDGEMENTS

The authors thank Peter Utz and Gabriel Marc from Geobrugg AG for their guidance, support, and practical insights throughout the work. The authors also thank Prof. Dr.-Ing. Alexander Michalski from HTWG Konstanz – University of Applied Sciences for academic supervision and constructive feedback.

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