Considering Fragmentation and Variability of Rockfall and the Third Dimension in Rockfall Barrier Design

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Abstract. At the end of the 1980s, the design, testing and subsequent manufacture of steel rockfall protection barrier systems began around the world. To ensure that these barriers can effectively stop the dynamic impact of rockfall, several guidelines have been introduced worldwide since 2001. The level of knowledge about the behaviour of rockfall protection barriers, and the current regulations related to their testing and remaining capacity after impact differ ay global level. In 2019 an Innosuisse-sponsored 3-year research project was awarded to WSL Institute for Snow and Avalanche Research SLF together with Geobrugg, from the industry side, for rockfall barriers full-scale testing, to deepen the knowledge about the variability of the actual behaviour of these protection barriers. The results lead to additional tests to the existing European certification procedure, allowing a better quantification of the energy capacity of the protective surface of rockfall barriers.

Keywords: rockfall barrier · field tests · eccentric testing · design reliability · 3D

1 Introduction to Rockfall Barrier Design

More than 30 years ago worldwide began the design, testing and subsequent manufacturing of steel barrier systems for rockfall protection. These barriers usually consisting of an infrastructure of posts and ropes, from which a flexible, usually ring-shaped, netting hangs. To ensure that these barriers can effectively stop the dynamic impact of rockfall, several guidelines have been introduced worldwide since 2001. They include proof of functional suitability through 1:1 field test, as well as proof of serviceability. In Europe, the approval and conformity verification procedures for rockfall protection nets, called ETAG 027, were introduced in 2008 [1]. In 2018, ETAG 027 was transformed into a European Assessment Document, EAD 340059-00-0106 [2]. According to this guideline, sets of tests will be performed for two energy levels: a Maximum Energy Level (MEL) and a Service Energy level (SEL), which represent a third of the MEL. The impact location is set for all three launches in the middle of the central functional module (see Fig. 1), representing the most favourable impact location for the barrier.

As can be seen in Fig. 1, the established impact is centred on the central functional module, however, the stresses that occur may be far from this ideal position, and this is

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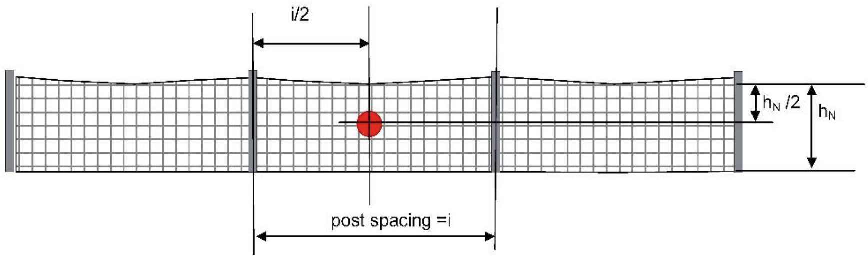

Fig. 1. Impact location established for the SEL and MEL launches, during certification tests (EOTA, 2018)

a latent concern. The performance of the vertical full-scale tests on the pre-established impact locations, does not allow that the rotation of the block in the natural ground to be considered. The understanding about the behaviour of rockfall protection systems, as well as the current regulations related to their testing and remaining capacity after impact, differ worldwide.

By exaggerating the problem, one can illustrate the problem with Figs. 2 and 3. Technically, according to [2], a barrier is fulfilling its retaining capacity over a certain area, in this case the middle of the middle field of the test system (see Fig. 2).

Any other kind of possible impact is not considered. Adversely, what is commonly expected of a rockfall barrier's protection surface? A fully covered area such as represented in Fig. 3. In some countries, specialised consultants are trying to solve the above problem by over-dimensioning the solutions and trying to extend the zone of effectiveness of the rockfall fence beyond the central area of the middle field established by the regulation. In some cases, engineers and decision-makers assume that the distribution of stresses is more efficient than reality, even when impacts occur in marginal areas. Taking all this into account, it can be said that systems are often not properly designed.

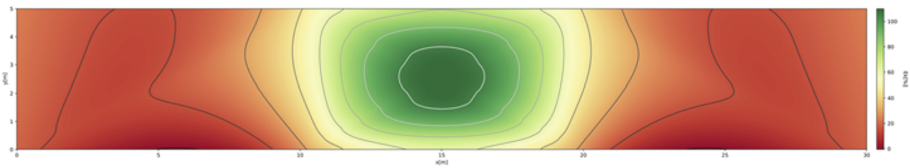

Fig. 2. Illustration of the energy capacity (in % of MEL) approximate distribution according to the normative regulation of centred impact location

Fig. 3. Illustration of the energy capacity (in % of MEL) approximate distribution according to the expectations of someone unfamiliar with the normative regulation

The transition from 2D to 3D rockfall simulations brings this topic back into the forefront when designing rockfall barriers, as the awareness increases that all possible impacts in the field must be taken into consideration along the length of the barrier.

2 Fragmentation of Falling Blocks Before the Barrier Hit

In recent years, interesting studies have been carried out on the fragmentation process of the blocks during their fall, for which studies have been carried out that include laboratory and field tests and simulations (Fig. 4). From the estimation of the family of joints of which the block is composed in origin and from the analysis of the movements, after calculating the size of the block that can be detached, it can be established accurately, what is the resulting fragmentation level once the block contacts the ground (depending on type of surface). This is undoubtedly a complex process that requires a very detailed knowledge of the slope geometry (DEM), as well as its properties. The estimation of the degree of fragmentation will make it possible to optimize the dimensioning process of the protection measure.

This possibility of blocks fragmentation makes the effective design of the barriers also demand the consideration of the third dimension, then to give an efficient response

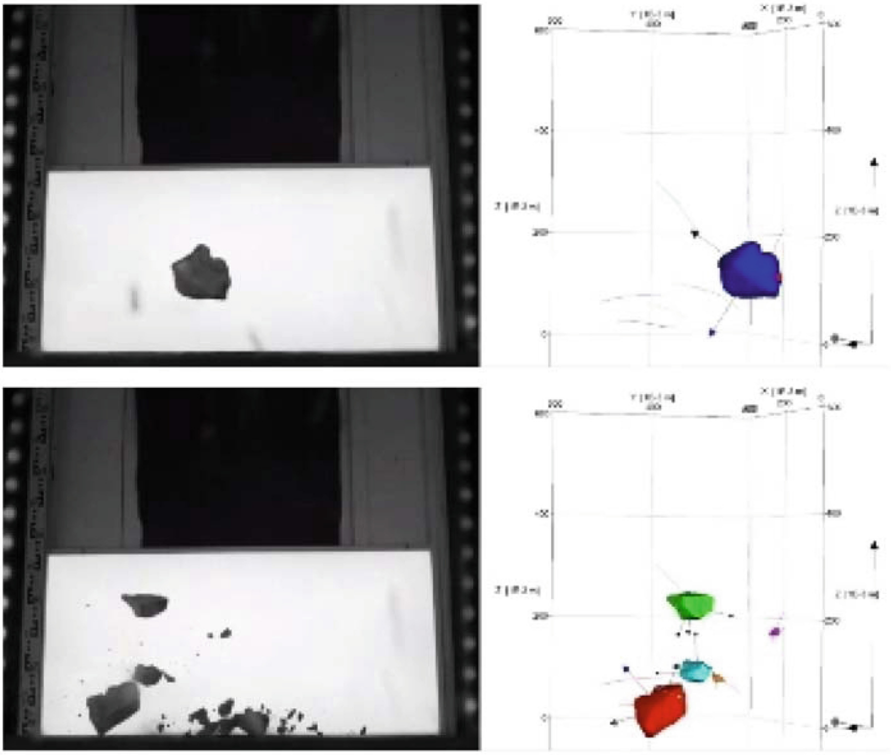

Fig. 4. Example of lab test of fragmentation impact [4]

to the problems of reality. This consideration of analysis is conclusive when it comes to rationally increasing the design safety factor.

3 Investigation of Rockfall Variability

In 2019 an Innosuisse-sponsored 3-year research project was awarded to WSL-SLF Institute for Snow and Avalanche Research together with Geobrugg, from the industry side, for rockfall barriers full-scale testing, to deepen the knowledge about the variability of the actual behaviour of these protection barriers to investigate in detail rockfall's unpredictability behavoiur and the blocks fragmentation process studied during last years. The tests series were carried out on a natural terrain at the Flüela Pass in the Swiss Alps. The main aiming of these experiments was to determine the maximum energy absorption capacity of these fence devices, using test techniques that are not covered by current standards and are closer to reality, while establishing which types of (repeatable) vertical tests could replace the performance to be able to make rational comparisons. Multiple tests were carried out in which standardised blocks of various shapes and dimensions, impacted a barrier placed downhill (Fig. 5). The rockfall barrier located the bottom of the slope was duly instrumented. Load sensors were used at different points of the structure to measure the tensions in the ropes and flexible anchors, as well as the loads on the ground bases. The standardised blocks used in the test series (up to 3200 kg) were also equipped with sensors to measure the angular velocity and acceleration on their way down the slope until impact the barrier surface. In addition, a drone equipped with a high-resolution video camera was used, as well as several stationary cameras, also of high resolution, which made it possible to record the trajectory and the moment of impact from different points of view. This has guaranteed the adequate reconstruction of the behaviour of the blocks and, most importantly, their interaction with the terrain in order to characterise the phenomenon [3].

Fig. 5. Example of a random eccentric impact into the instrumented rockfall barrier during a field test campaign

4 The Third Dimensioning in Relation to the Barrier's Protection Surface

In some of the tests carried out, disc-shaped blocks were used to recreate the characteristics of the site in terms of available material and topography. Undoubtedly, this block shape promotes an increase in angular velocity, which will allow further analysis in the impact zones to be considered in the design [3]. As was to be expected, test blocks travelling with a high rotational energy component can cause impacts loads on the barrier that are not contemplated in the normative testing process and therefore in the certification, according to the European Assessment Document (EAD). The barrier length must necessarily be adapted based on the possible trajectories. Logically, disc-shaped blocks promote a much higher lateral dispersion than regular blocks, therefore the probability of impact in the lateral functional modules is greater [3]. The main danger is the possible increased of the forces on the barrier surface, that that is not able to absorb higher tangential forces and fails.

Two substitute loads that guarantee the best possible coverage along the entire length of the barrier line were, therefore, determined to reproduce the tangential forces caused by the rotation and consider border field hits. These additional tests lead to a new assessment of the energy capacity absorption of the protection surface of a rockfall barrier. The results of this tests are highlighted in Fig. 6.

With these results of the research project [3], the dimensioning in 3D of a rockfall barrier can now be considered in more detail. Knowing what a rockfall barrier is tested for, makes it easier to plan the third dimension, as illustrated in Fig. 7. It can be said that it is possible to take the barrier performance into account on its overall length. While the goal must be to give the designer a tool to have more planning security.

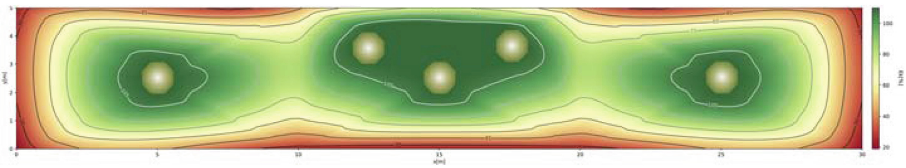

Fig. 6. Illustration of the theoretical energy distribution (in % of MEL) on the surface of the barrier, implementing the experience of the test results on the natural slope, to the vertical test, see impacts on critical points

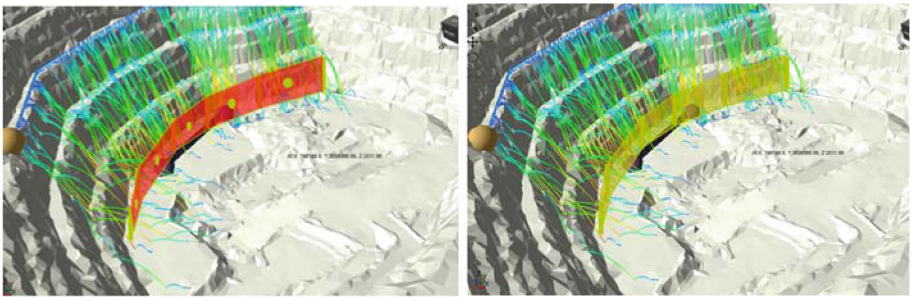

Fig. 7. Hypothetical example of the dimensioning of a rockfall project in 3D. With the performance of a barrier simply assessed by the EAD [2], the left image shows the theoretical energy capacity uptake. No planning security is given on non-standardized impacts. With a greater knowledge of the energy uptake of a barrier, the dimensioning could look like on the right image [5]

5 Conclusion

It can be concluded that the current regulation EAD 340059-00-0106 does not consider some important behaviours of the rockfall phenomenon, such as the influence of the shape and dimensions of the blocks, as well as the very probable impact of the same, in a critical area within the protection system. The tests carried out in the Swiss Alps allow us to confirm that there is a specific load combination, among which is the angular speed of the blocks and the variation in the trajectories, which cause impacts near the posts and in extreme modular sections of the barrier, cause real behaviours, different from those considered by said regulation. It has undoubtedly been shown that the trajectories achieved are more dispersed and have a great influence on the definition of the total length of the protection. Considerations of the possible fragmentation of the blocks make the need to achieve effective systems against multiple impacts and impacts in critical areas a reality. The use of 3D simulation tools allows the designer to accurately consider the trajectories of the disc-shaped blocks, even in the case of blocks of regular dimensions, when the roughness of the surface is high, the rebounds can influence in the dimensioning of the height of the barrier. Adding this proposal to the current knowledge base allows for a rational and effective design of landslide protection systems.

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