A hybrid structure to protect infrastructures from high energy rockfall impacts

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ABSTRACT: The need of structures able to stop large moving blocks requires impact mechanics studies coupled with capacity design. Among natural phenomena, rockfall probably is the most hazardous due to its abruptness and high energies involved. Rock blocks can impact a structure even with a kinetic energy of 50 MJ, developing extremely large forces and involving consistent damages. To protect inhabited areas and infrastructures, mitigation measures are installed along slopes. Focusing on protective measures, several solutions can be adopted, i.e., net fences, embankments, rigid barriers, etc. Such structures intercept and stop the falling block by dissipating its kinetic energy through permanent large deformations. The performances of the systems are different and depend on the adopted technology. Net fences with dissipators can stop blocks up to 10000 kJ, but they need large downslope free area. RC walls alone are not diffused as they cannot withstand rockfall impact forces. Although reinforced earth embankments are a profitable solution for the high capacity (up to 50 MJ), their geometry represents a strong constraint because of large width and heavy weight. We propose a compelling solution for protecting infrastructures with a hybrid structure made of multiple vertical layers: a high deformable downhill earth face coupled with a RC wall. This solution ensures energy dissipation and reduced deformability of the downslope face of the structure and can be installed close to roads. A simplified design procedure and an example are proposed with reference to a real case study. The effectiveness of the rockfall risk mitigation measures is discussed and a cost-energy capacity design chart is presented.

1 INTRODUCTION

Rockfall events can represent one of the most hazardous among the landslide phenomena (Scavia et al. 2020). Due to high possible damages, protective measures are often required, e.g. net fences and rockfall protection embankments (RPE). While the former can sustain impacts up to 10000 kJ, rockfall protection embankments (RPE) have been considered a suitable solution especially against rockfall events involving very high kinetic energies, up to 50 MJ, together with their ability to sustain repeated impacts before collapse (Lambert & Kister 2017). Among the advantages, their easiness of maintenance and of repair after impacts, high durability in time, as well as their reduced environmental impacts should be addressed. Nevertheless, their massive size needs a suitable topographical configuration in terms of space and inclination of the site. The overall stability of the slope has to be verified, as well as, the possibility of material retrieval and handling and the construction difficulties should be assessed.

Different types of embankments have been developed in the past, differing for shape and for materials of uphill, core, and downhill faces (Lorentz et al. 2006). Among them, the reinforced earth RPE, i.e., a system made up of overlaid layers of compacted soil, each wrapped in a tensile resistant element, represents a valuable solution, allowing a side inclination up to 70°. At equal self-weight, structures higher than the simple earth ones can be realized through this technology. In general, in reinforced earth RPE, half of the structure (the uphill part) serves for energy dissipation through compaction and plasticization. In general, the downslope half serves for supporting the displacement as the impacted layers move one over the others in downhill direction dissipating the remaining kinetic energy into friction.

Rockfall protection structures are well diffused along transportation routes to protect vehicles/trains, etc. or in proximity of urbanized areas. Net fences, which are usually preferred since they are easy to install and have low visual impact, dissipate energy through large displacements, sometimes more than 5 m, requiring the need of a minimum distance from the element at risk. Earth embankments might require a large foundation area and have specific constraints in the installation. In addition, the designer must provide addition free space for the deformation during the impact (Fig. 1).

In the present work, a compelling solution is proposed for protecting infrastructures with a hybrid structure made of two vertical layers: a high deformable uphill face made of reinforced earth coupled with a downhill reinforced concrete (RC) wall. In the following, a design scheme to support impact loads is proposed. The analyses are based on the results of experiments and studies on rockfall protection tunnels, i.e., structures where a granular medium is installed over an underneath rigid stratum (Schellenberg & Vogel, 2009). In Section 2, the engineering solution is described, while in Section 3 the proposed design method is presented. Parametric analyses and a discussion about the economic advantages in installing such coupled rockfall protection structure are reported in Section 4 and 5, respectively.

Figure 1. In the top, view of a rockfall net fence along a road. In the bottom, view of a rockfall earth embankment.

2 THE HYBRID ROCKFALL PROTECTION STRUCTURE

The herein proposed rockfall protection structure consists in an earth reinforced embankment laterally supported by a RC structure, i.e., a wall. The uphill earth face is realized with horizontal layers of compacted soil wrapped by a plastic geogrid. Each layer has a heigh of about 60 cm, as suggested in the common practice (EN 14475 2006). This technology allows steep faces. The presence of reinforcements, i.e. geogrids, serves to guarantee higher slope of the uphill face and, consequently, to save space and material. The obtainable slope angle is generally between 60° and 75°. In the present case, the slope of the uphill face, only, is about 70°, while the vertical downhill earth face is in contact with the uphill concrete surface. The RC wall has the same height of the earth part and has a constant thickness. The system lays over a reinforced concrete foundation slab, eventually with foundation piles, depending on the forces involved and the overall soil characteristics. Figure 2 sketches the hybrid structure.

As detailed in the specific sections, in the proposed structure, block kinetic energy is dissipated in the earth layer (only through compaction) and the resulting forces are turned into pressures on the concrete wall.

Differently from a simple reinforced earth RPE, the proposed solution presents limited site constraints since the overall cross-section is reduced. In addition, no downhill displacements occur, thus, it can be installed closer to the road infrastructure. On the opposite, due to its reduced cross-section, the toppling must be verified and foundation piles are sometimes necessary to stability.

In the following, the design of the structure is discussed focusing on the impact resisting mechanisms, only.

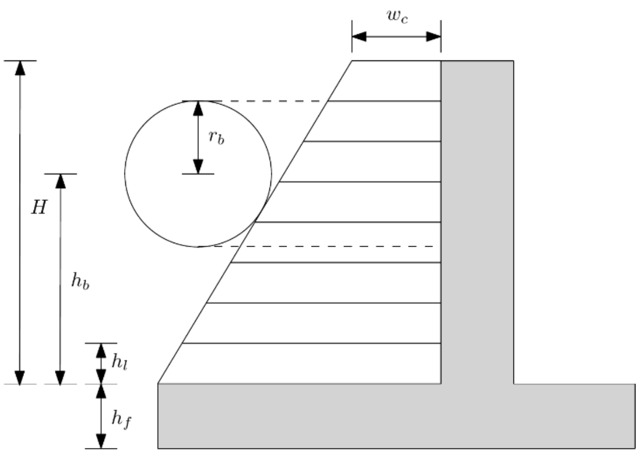

Figure 2. Sketch of the hybrid rockfall protection structure.

3 METHODOLOGY

In this section, a simplified method to evaluate the effects of the actions due to the impact of a block on the hybrid protection structure is illustrated. To this aim, the dynamic design situation is considered, only. The proposed design method derives from the procedures adopted for rockfall protection tunnels (Labiouse et al. 1996, Montani 1998, Astra 12 006 2008, Calvetti & Di Prisco 2009), in which the reinforced concrete structure is covered by a granular soil stratum. In this system, the block impacts and penetrates the soil layer, which should be deep enough to avoid direct contact on the concrete structure and to allow stress diffusion. During the penetration, dissipation of kinetic energy occurs. Following the guidelines, the concrete structure is thus designed to sustain an equivalent load (Astra 12 006 2008).

The hybrid structure herein proposed can thus be considered as a system composed by two vertical layers, whose properties are similar to those of rockfall protection tunnels.

To design the hybrid rockfall protection structure, the mechanical uncoupled response of the system is studied. Thus, the forces in the earth component are the loads acting on the RC part. In detail, the overall design is performed according to the following steps: (i) by evaluating the impact force acting on the block-earth interface, (ii) by computing the penetration of the block in the earth layer, (iii) by computing the pressures acting on the RC wall, assuming a horizontal force propagation through the vertical earth layer; (iv) by providing adequate structural capacity to the RC structure. In the following, the design steps are detailed.

3.1 *Reinforced earth layer*

In this paragraph, the maximum force exerted by the block on the soil is evaluated. Following the findings of experimental studies on reinforced earth protection embankments (Peila et al. 2007, Ronco et al., 2009), the stress geometrical diffusion (the zone disturbed by the impact) is evaluated and the equivalent load acting on the RC wall is computed.

The upslope earth layer serves as a cushioning stratum, with the function of dissipating the kinetic energy of the block through soil compaction and diffusing the loads. It follows that the penetration of the block has to be computed, as well as the maximum dynamic force at the block-earth interface.

As mentioned before, the maximum force $F_{E,max}$ is evaluated considering the findings of laboratory tests performed on concrete slabs covered by granular soil (Labiouse et al. 1996, Montani et al. 2004, Lorentz et al. 2005). Among the formulations, the one proposed by Montani (1998) is the most suitable, as revealed by the experiments and numerical simulations on RPE (Peila et al., 2007):

$$F_{E,max} = 2.8t^{-0.5} r_b^{0.7} M_E^{0.4} tan\phi E_k^{0.6} \quad (1)$$

where t is the thickness (in meters) of the earth layer in the point of the impact (considering the center of mass of the block), r_b the block radius (in meters), M_E the elastic modulus of the soil (in kPa), ϕ the internal friction angle, and E_k the kinetic energy of the impacting block (in kJ). It is worth mentioning that E_k should be obtained by accurate rockfall propagation analyses, considering reference values in the distributions of both the mass m_b and the velocity of the impacting blocks v_b.

Layer deformation δ_E, i.e., compaction of the soil and crater formation, can thus be evaluated as the ratio of twice the kinetic energy and the correspondent resistant force, assuming that a linear compaction force-displacement relationship holds until the maximum force $F_{E,max}$ is reached:

$$\delta_E = \frac{2E_k}{F_{E,max}} \quad (2)$$

From the crater, a diffusion of the stresses is considered. Experimental studies on RPE reveal that an horizontal diffusion of 45° can be achieved (Yoshida 1999, Ronco et al. 2009, Maegawa et al. 2011), while the vertical diffusion has a lower angle of aperture ψ_v (Lambert et al. 2014) and it is limited by the structure height. Assuming a spherical block, the area on the earth-concrete interface influenced by the impact A_{RC} can be assumed as rectangular whose horizontal side length is equal to $(2t + 2r_b)$, while the vertical side length is equal to $(2t\ \tan\psi_v + 2r_b)$, where ψ_v can be assumed equal to 30°. The vertical side height must be limited to the system height, depending on the point of impact.

3.2 *Reinforced concrete wall*

The pressure acting over the upslope face of the RC wall is assumed as unform over the area on the earth-concrete interface influenced by the impact and is equal to:

$$q_{RC} = \frac{F_{E,max}}{A_{RC}} \quad (3)$$

Considering the wall as a cantilever, the maximum forces (bending moment and shear) are recorded at the base. The usual approaches proposed in the design codes allow to define the thickness of the RC wall and to quantify the amount of reinforcement to support the acting forces.

4 PARAMETRIC ANALYSES

The kinetic energy of the block E_k, namely ½ $m_b v_b^2$, is the key parameter in rockfall engineering, as well as the height of the impacting block. The parametric analysis for defining the capacity of the system to mitigate rockfall hazard considers variable block size (thus, the mass) and block impacting velocity. The sample structure has the sizes and properties reported in Table 1.

Table 1. Sizes and properties of the sample hybrid structure.

Parameter	Value
Height, H	4.8 m
Single layer height, h_l	0.6 m
Top earth width, w_c	2.0 m
Uphill slope angle	70°
Foundation height, h_f	1.5 m
Elastic modulus of the soil, M_E	25 kPa
Internal friction angle, ϕ	30°
Concrete compressive strength, R_{ck}	37 MPa
Steel reinforcement yield strength, f_{yk}	450 MPa

Starting from the idea that the worst impact situation occurs when the block impacts near the very top of the structure, but following the design rule proposed in Marchelli & Deangeli (under review), the height of the impacting block h_b was considered as:

$$h_b = H - r_b - h_l \quad (3)$$

where H is the total height of the structure, while $h_l$is the height of each layer of compacted soil.

A set of simulations was performed in order to evaluate the q_{RC} for different impact energies, i.e., for variable r_b and v_b. In particular r_b ranges from 0.5 m to 1.5 m, i.e., for a spherical block from about 0.5 m^3 to 14 m^3, while v_b is taken from 5 m/s to 30 m/s. Consequently, the involved kinetic energy E_k spans from about 18 kJ to 17670 kJ. The contour plot in Figure 3 illustrates the obtained value of q_{RC}, ranging from 7 kPa to 427 kPa in the worst case.

The resulting forces on the RC wall were computed according to the geometric diffusion previously described resulting in bending moment and shear at the base, i.e., the most solicited cross-section. The RC wall was designed considering a fixed reinforcement area equal to 1% of the concrete cross-section size. The minimum wall thickness is obtained considering that the flexural capacity of the structure should be equal to the bending moment acting at the base.

Figure 4 depicts the bending moment M_{RC} at the base for various kinetic energies and impacting block sizes. It results that the curves can be superimposed, thus the forces in the RC wall are not dependent on the size of the impacting element but mainly vary on the kinetic energy.

Following the impact forces, then obtained minimum thicknesses of the RC wall range from 0.15 m (theoretical) to 1.2 m.

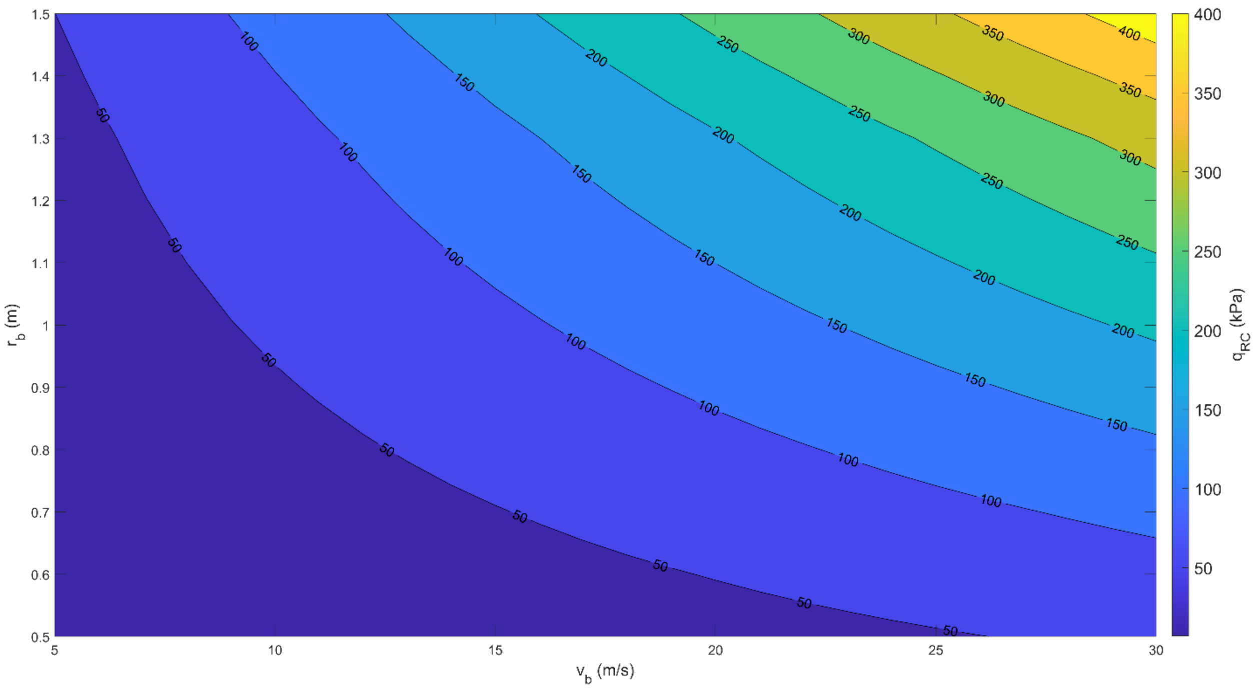

Figure 3. Pressure over the upslope face of the concrete wall q_{RC} for different rockfall block radii and impacting velocities.

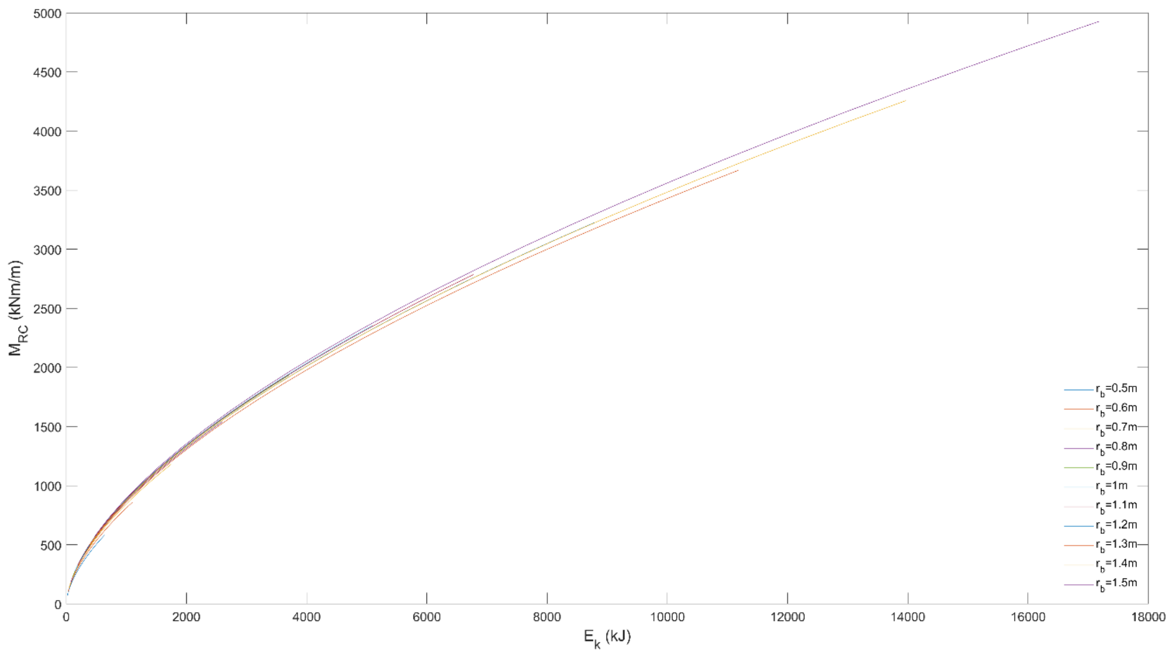

Figure 4. Bending moment at the base of the reinforced concrete wall for various kinetic energies.

5 DISCUSSIONS AND CONCLUSIONS

The parametric analysis herein presented reveals that the system can support an impact of maximum kinetic energy smaller of 17 MJ with an area occupation of about 5 m wide. The energy capacity has to be considered as the ultimate limit one. This results in a possible solution for road protection systems, since a reduced occupation area is needed. It must be noted that the hybrid system has also the advantage that easy maintenance works are required after impacts with energy lower than the design one. This can be obtained by simply refilling the crater with earth, restoring the design thickness of the earth layer.

To assess the economic sustainability of the proposed solutions, construction costs of the most recurrent rockfall protections structures are compared. The Figure 5 reports the cost of one meter long protection structure for various kinetic energies resulting from price lists for Europe.

It is shown that from an economic point of view the hybrid structure can be comparable with both net fences and reinforced earth RPE.

To conclude, the present paper intends to highlight the possibilities of using modified existing structures as new rockfall protection systems. In particular, the dissipation properties of earth embankments are coupled with strong horizontal capacity of reinforced concrete walls. The system has the main advantage of having no deformation on the downslope size, thus it is possible to put it close to the protected element. The study herein presented is preliminary. Further analyses should be performed to details the characteristics, the weaknesses of the proposed solution.

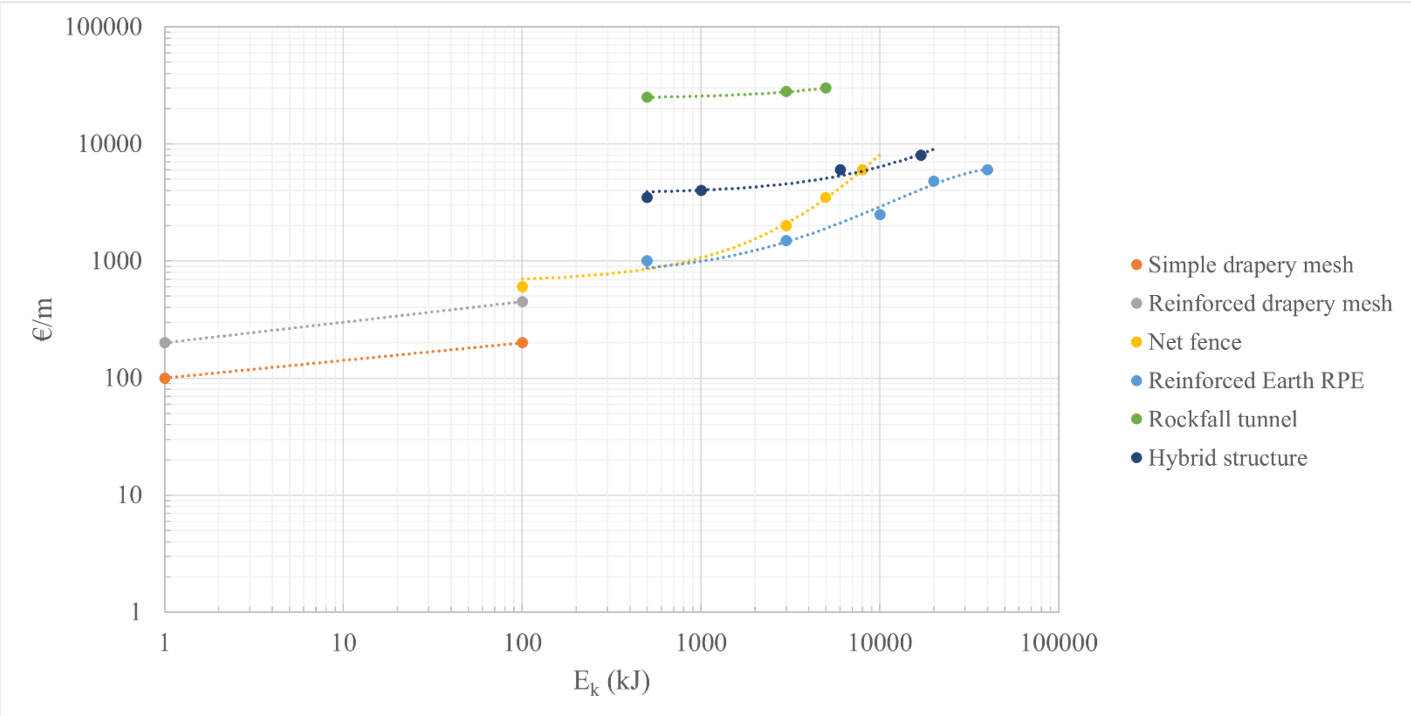

Figure 5. Prices of the most common rockfall mitigation measures, considering a mean height of 5 m.

REFERENCES

ASTRA 12 006 2008: *Actions de chutes de pierres sur les galeries de protection*. Office Fédéral des routes OFROU, Berne, Switzerland.

Calvetti, F., & di Prisco, C. 2009. An uncoupled approach for the design of rockfall protection tunnels. *Structural engineering international*, 19(3), 342-347.

EN 14475 2006. *Execution of special geotechnical works – Reinforced fill*. CEN European Committee for Standardisation, Brussels, Belgium.

Labiouse, V., Descoeudres, F., & Montani, S. 1996. Experimental study of rock sheds impacted by rock blocks. *Structural Engineering International*, 6(3), 171-176.

Lambert, S., Heymann, A., Gotteland, P., & Nicot, F. 2014. Real-scale investigation of the kinematic response of a rockfall protection embankment. *Natural Hazards and Earth System Sciences*, 14(5), 1269-1281.

Lambert, S., and Kister, B., 2017. Analysis of Existing Rockfall Embankments of Switzerland (AERES); Part A: State of Knowledge. Federal Office for the Environment, Bern. 1-55.

Lorentz, J., Donzé, F. V., & Plotto, P. 2005. Experimental investigation of the dissipative efficiency of a multilayered protective structure against rockfall. *Discrete Element Group for Risk Mitigation*, 83.

Lorentz, J., Donzé, F. V., Perrotin, P., & Plotto, P. 2006. Experimental study of the dissipative efficiency of a multilayered protective structure against rockfall impact. *Revue européenne de génie civil*, 10(3), 295-308.

Maegawa, K., Tajima, T., Yokota, T., Tohda, M., 2011. *Slope-rockfall tests on wall embankments reinforced with geosynthetics*. Proceedings of the 6th International Structural Engineering and Construction Conference, Zürich, Switzerland, pp. 641–646.

Marchelli, M. & Deangeli, C. (under review). Towards a codified design procedure for rockfall reinforced earth embankments. *GEAM*

Montani Stoffel, S. 1998. Sollicitation dynamique de la couverture des galeries de protection lors de chutes de blocs (master Thesis). EPFL.

Montani Stoffel, S., Labiouse, V., & Descoeudres, F. 2004. Impatti di blocchi rocciosi su un modello di galleria di protezione caduta massi. *GEAM*: 279-293.

Peila, D., Oggeri, C., & Castiglia, C. 2007. Ground reinforced embankments for rockfall protection: design and evaluation of full scale tests. *Landslides*, 4(3), 255-265.

Ronco, C., Oggeri, C., & Peila, D. 2009. Design of reinforced ground embankments used for rockfall protection. *Natural Hazards and Earth System Sciences*, 9(4), 1189-1199.

Scavia, C., M. Barbero, M. Castelli, M. Marchelli, D. Peila, G. Torsello, and G. Vallero. 2020. Evaluating Rockfall Risk: Some Critical Aspects. *Geosciences* (Switzerland) 10 (3): 1–29.

Schellenberg, K. 2008. *On the design of rockfall protection galleries* (Doctoral dissertation, ETH Zurich).

Schellenberg, K., & Vogel, T., 2009. A dynamic design method for rockfall protection galleries. *Structural Engineering International*, 19(3): 321–326.

Yoshida, H., 1999. *Recent experimental studies on rockfall control in Japan*. Proceedings of the Joint Japan-Swiss Scientific Seminar on Impact Load by Rock Fall and Design of Protection Structures, Kanazawa, Japan, 69–78.