



**HAL**  
open science

# On the efficiency of protection structures against gravity-driven natural hazards

Stéphane Lambert

► **To cite this version:**

Stéphane Lambert. On the efficiency of protection structures against gravity-driven natural hazards. Engineering Sciences [physics]. Univ. Grenoble Alpes, 2020. tel-03048918

**HAL Id: tel-03048918**

**<https://hal.science/tel-03048918v1>**

Submitted on 18 Dec 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# On the efficiency of protection structures against gravity-driven natural hazards

Stéphane LAMBERT

October 2020



## Foreword

This document constitutes a public version of the dissertation wrote in view of obtaining my accreditation to direct research (*Habilitation a diriger des recherches, HDR*).

The defense took place on the 31st of August 2020 before a jury composed of Anna Giacomini (Professor, UON), Laurent Baillet (Professor, UGA), Jean-Yves Delenne (Research Director , INRAE), Claudio di Prisco (Professor, Polimi) and Olivier Gagliardini (Professor, UGA) to whom I express my sincere thanks.

This document makes a synthesis of works conducted over the last 13 years in INRAE Grenoble (formerly Cemagref, then Irstea).

I wish to express my warm thanks to all the people who have contributed to these works, from the technical staff in INRAE to the numerous people cited in the following.



# Contents

<b>1</b>	<b>Protection against gravity-driven natural hazards in mountain areas</b>	<b>1</b>
1.1	Context . . . . .	1
1.2	Civil engineering protective structures . . . . .	2
1.2.1	Rockfall protection embankments . . . . .	2
1.2.2	Flexible barriers . . . . .	3
1.3	Design outlines . . . . .	4
1.3.1	General . . . . .	4
1.3.2	Design of RPEs . . . . .	5
1.3.3	Design of flexible barriers . . . . .	6
1.4	A contribution to the improvement of design practices . . . . .	7
1.5	Manuscript content . . . . .	9
<b>2</b>	<b>Towards an advanced design of rockfall protection embankments</b>	<b>11</b>
2.1	Introduction . . . . .	11
2.1.1	Motivations . . . . .	11
2.1.2	Sandwich RPEs . . . . .	11
2.2	Half-scale structure impact response . . . . .	12
2.3	Real-scale structure impact response . . . . .	14
2.3.1	Sandwich structure as embankment facing . . . . .	16
2.3.2	Free-standing sandwich structures . . . . .	18
2.4	Synthesis . . . . .	20
<b>3</b>	<b>Modelling flexible barriers for design improvement purpose</b>	<b>23</b>
3.1	Introduction . . . . .	23
3.2	Debris flows catchment barrier . . . . .	24
3.2.1	Context . . . . .	24
3.2.2	Flow model . . . . .	24
3.2.3	Barrier model . . . . .	25
3.2.4	Structure response . . . . .	26
3.2.5	Conclusion . . . . .	29
3.3	Rockfall protection barriers . . . . .	29
3.3.1	Context . . . . .	29
3.3.2	Improved ring model . . . . .	29

3.3.3	Modelling of the curtain effect . . . . .	30
3.3.4	Model predictive capabilities . . . . .	31
3.4	Synthesis . . . . .	33
<b>4</b>	<b>Assessing the efficiency of protection structures</b>	<b>35</b>
4.1	Introduction . . . . .	35
4.2	Rockfall protection embankments . . . . .	36
4.2.1	Impact strength assessment criterion . . . . .	36
4.2.1.1	Context . . . . .	36
4.2.1.2	Proposed criterion . . . . .	36
4.2.1.3	Application to existing RPEs . . . . .	38
4.2.1.4	Concluding remark . . . . .	38
4.2.2	Ability in controlling rock blocks trajectories . . . . .	40
4.2.2.1	Context . . . . .	40
4.2.2.2	Developed solution . . . . .	40
4.2.2.3	Application to a real case . . . . .	41
4.3	Flexible barriers . . . . .	42
4.3.1	Context . . . . .	42
4.3.2	Two-parameter probabilistic design . . . . .	43
4.3.3	Metamodel-based approach . . . . .	45
4.3.4	Application to real cases . . . . .	49
4.3.5	Concluding remark . . . . .	51
4.4	Synthesis . . . . .	51
<b>5</b>	<b>Ongoing projects</b>	<b>53</b>
5.1	Articulated rockfall protection wall . . . . .	53
5.2	Barriers in torrential context . . . . .	54
	<b>Bibliography</b>	<b>59</b>

# Chapter 1

## Protection against gravity-driven natural hazards in mountain areas

### 1.1 Context

Mountain is a fascinating universe by the beauty of the landscapes it offers to our eyes, the rudeness of the environment and the proximity to the sky. Mountain is a place where humans feel free and humble. Nevertheless, mountains are also a place where humans are exposed to gravity driven natural hazards such as rockfall, snow avalanches and debris flows.

These natural hazards threaten human lives, buildings and activities. People are killed or injured, housing and infrastructures are damaged or destroyed, traffic on roads and railways are interrupted. This latter consequence is particularly critical in mountain areas where traffic corridors are highly constrained by topography.

The prediction and the mitigation of these hazards in particular question the departure area location, occurrence prediction, propagation speed and characteristics of the elements at risk. The mitigation of these natural hazards often relies on different approaches including preventive and protective measures. The formers may consist in informing or evacuating exposed people. The latter may consist in building protective structures, for example. For a given site, the best mitigation strategy is defined considering notably the frequency and magnitude of the considered event, the site topography, the characteristics of the elements at risks, the acceptable hazard and the mitigation cost.

The growing urbanisation of mountain areas coupled to an increase in risk aversion, in a context with strong economic constraints, have been boosting the demand for an improved risk management for a couple of decades. In addition, the current context of climate change seriously questions the appropriateness of current practices in terms of risk assessment and management. Indeed, some gravity driven natural hazards are experiencing a significant evolution, in terms of occurrence and magnitude, that was correlated to global warming (rockfall, snow avalanches). This evolution in particular poses the question of the efficacy of existing mitigation strategies.

The continuing and increasing societal demand for an improved risk mitigation motivates research on the efficiency of protection structures against gravity-driven natural hazards, in particular. This demand refers to the improvement of design methods and the development of new technologies, in view of reducing costs while improving hazard reduction.

## 1.2 Civil engineering protective structures

There exist a wide variety of protective structures against gravity driven natural hazards specific to mountain areas. In the following, focus is placed on flexible barriers and embankments, with application to the protection against rockfall for the latter, and also against debris flows for the former.

### 1.2.1 Rockfall protection embankments

Rockfall protection embankments (RPEs) are massive earthworks, built down the slope with the aim of intercepting or deviating rock blocks before reaching the elements at risks. In this manuscript, any structure in elevation of at least 2m with respect to the ground, mostly made of granular materials (soil, gravel...) is considered as a rockfall protection embankment (RPE), whatever its cross sectional shape (Fig. 1.1). Most often, the RPE is associated to a ditch, aiming in particular at collecting fallen rock blocks and debris.

RPEs are appropriate when medium- to very-high-kinetic-energy events are expected, from a few hundred kilojoules to tens of megajoules. They are preferred over flexible barriers when the design impact is higher than 5000 kJ. The other declared advantages are low maintenance costs and reduced visual impact. Nevertheless, they are not appropriate on steeper slopes and their construction generally requires extensive space and accessibility for engines. Generally, the ditch is dug in the slope uphill from the RPE and the cut materials are used to erect the RPE.

The variety of RPEs types has considerably increased over the last two decades, employing different types of construction materials (Fig. 1.1). Some of these structures are presented in technical publications (see references in Lambert and Bourrier [2013]). Most of the developments over the last decades concern soil-reinforced structures, using horizontal inclusions such as geosynthetics with the aim of increasing the RPE impact strength as well as the steepness of its front face.

In some countries, large rockfall protection embankments collections exist. France and Switzerland cumulate more than 600 RPEs, with more than 200 embankments registered and well documented in each of these two countries [Lambert and Kister, 2017b; Lambert, 2012]. Maximum reported length and height are 700 m and 13 m respectively. For what concerns France, the cumulated length of the inventoried structures exceeds 50 km. These structures protect elements at risks against rockfall with kinetic energies mainly in the 2000-20,000 kJ range. The protection role assigned to RPEs is thus major.





**Figure 1.1** Various types of rockfall protection embankments, in terms of geometry, dimensions and constitutive materials. (for references, see Lambert and Bourrier [2013]).

### 1.2.2 Flexible barriers

In the context of protection against natural hazards in mountain areas, the term flexible barrier refers to any kind of structure made of metallic components and acting as passive protection structure to intercept debris flows, snow avalanches and rockfalls or as active protection structures to prevent the snow mantle from sliding on the slopes (snow fence). The very first use of flexible barriers for intercepting rockfall dates back to the 1970's. These structures are the most often used for protecting against rockfall. The most recent widespread application appeared in the middle of the 2000's and concerns debris flows catchment barriers.

Flexible barriers consist of an interception structure, a support structure and connecting components (Fig. 1.2) and are made from posts, net elements, sliding rings, main cables, lateral cables, shackles, energy dissipating devices and lateral anchors. Energy dissipating devices (also referred to as brakes) are key components in the barrier response. Their large plastic deformation results allows dissipating part of the impact energy damping while reducing loads transiting via the cables towards the anchors.

Often, the interception structure consists of a repeated pattern of interlaced steel rings (Fig. 1.2) but other mesh types are also used, with various unit mesh shape and size (double-twisted, square, diamond, water drop...). Important differences also concern energy dissipating devices, whose technology, number and layout in the structure greatly differ from one structure type to the other [Castanon-Jano et al., 2017]. Difference also concern the cables



**Figure 1.2** Illustration of the variety of flexible rockfall protection barriers.

layout and connection between the interception structure and the support structure. Last, these various components are mainly made from metal but other materials such as wood or polymers are occasionally used for part of the structure elements. The components characteristics and their layout in the structure heavily depend on the manufacturer, the concerned hazard and the site configuration. There is thus a wide variety of flexible barriers, and consequently a wide variety of response of these structures when exposed to loadings by rockfall, debris flows or snow.

The main advantage of flexible barriers over other rockfall or debris flows protective structures are their high deformation capacity and their water permeability. They are advantageous for their short construction times and ease of installation in hard-to-reach terrains. In comparison with more rigid rockfall protection structures, they distribute the impact energy over longer impact durations and thus reduce the loads induced in the structure.

## 1.3 Design outlines

### 1.3.1 General

The design of protective structures aiming at mitigating natural hazards in mountainous areas consider two main specific facets. The first one addresses the ability of the structure in adequately controlling the displacement or propagation of the concerned natural event (debris flow, rockfall, snow). The second concerns the ability of the structure in resisting the loading resulting from the interaction with this natural event. These two design facets are often referred to as 'functional design' and 'structural design', respectively. The design

of protection structures also addresses more classical issues such as the foundation strength, the talus slope stability, the internal stability of earthen structures with respect to gravity loadings, the interaction with other natural flows (surface run-off, torrent, debris flow, water source, snow avalanche), the visual perception and environmental impact flora and fauna.

As for passive rockfall protection structures (RPEs and flexible barriers), the functional design aims at defining the structure height in view of intercepting the design rockfall while the structural design questions the strength of the structure to the rock block impact. For both these design facets, input data concerning the design event are issued from rockfall trajectory simulations and concern the rock block passing height and its kinetic energy at the structure location. For these parameters, it is often recommended to use the 95% percentile of the corresponding distributions for describing the design event.

Design methods, guidelines and standards were proposed in some countries for both design facets and both structure types. These are in particular based on research and development works conducted worldwide over the last 30 years and involving experiments and numerical simulations. Nevertheless, these are few and some are flawed. Also, there is still a large gap between knowledge and practices, because research results partly percolate down to engineering practices.

### 1.3.2 Design of RPEs

The few design methods available from the technical literature, national guidelines and recommendations principally concern the structural design and were published since the late 2000's [Lambert and Kister, 2017a]. The structural design approaches accessible to design engineers differ in their level of complexity and ability in accounting for the dynamic loading, as resulting from the rock block impact. The different types of approaches may be classified as follows (abridged from [Lambert and Kister, 2017a]):

- Type 1: no consideration for the dynamic loading. The RPE is assumed to be able to withstand the impact thanks to its mass.
- Type 2: determination of an admissible value for the maximum rock block penetration in the RPE face.
- Type 3: accounting for a static force, equivalent to the dynamic loading, for conducting a classical geotechnical design.
- Type 4: comparison of the energy dissipative capacities of the RPE with the incident rock block kinetic energy.
- Type 5: numerical modelling.

The currently proposed analytical design methods (types 2 and 3) mainly rely on the determination of the impact force on the embankment. Nevertheless, the various approaches proposed for estimating the impact force were shown to exhibit strong limitations, resulting in

a scattering of the impact force estimate in a ratio of 1 to 4 from one method to another when applied to a same case [Lambert and Kister, 2017a]. Besides, surveys revealed that the vast majority of RPEs built in France and Switzerland were designed without any consideration for the dynamic nature of the loading [Lambert, 2012; Lambert and Kister, 2017b, 2018].

In the end, the design methods accounting for the dynamic loading are globally few, were proposed recently, are not completely reliable and are rarely used by design engineers. This latter point in particular results from the fact that most of these works did not percolated down to practitioners.

The current and growing demand from operational stakeholders concerns optimized RPEs with reduced foot print compared to traditional designs. Indeed footprint is a particularly strong constraint when dealing with transportation corridors at the toe of steep slopes in narrow valleys.

As for the functional design of RPEs, existing recommendations concern the definition of the RPE height and front face inclination. The RPE height is determined based on the design block passing height increased by a free board. This latter is generally expressed as a multiple of the block radius. The aim is to avoid impacts close to the crest, that increase the risk of block over topping or rolling over the structure [Mölk and Hofmann, 2011; Breugnot et al., 2016]. The inclination of the front face of the RPE is recommended to be high enough in order to reduce the risk of rolling over. In France, a steepness of at least  $65^\circ$  is recommended [Calvino et al., 2001] but steeper inclinations are sometimes mentioned in specific studies [Simons et al., 2009]. It is worth highlighting that these recommendations are essentially based on empirical knowledge, with very limited support from research works. There is thus a potential need for improving the methods for evaluating the efficiency of embankments in controlling the blocks trajectory, for instance based on optimized trajectory simulation tools.

### 1.3.3 Design of flexible barriers

In day-to-day practice, the structural design of rockfall flexible barriers is essentially based on the barrier capacity determined following the European assessment document (EAD) dedicated to rockfall protection kits [EOTA, 2018]. This EAD prescribes real-scale experiments consisting in normal-to-the-barrier impacts by a projectile without rotational velocity, on the central panel of a three-panel barrier. Two block kinetic energies at impact are considered.

This test is a conformance test, in that the provided barrier capacity relates to the barrier response in these two impact conditions, and doesn't account for the variability in loading cases observed in the field. Impact with rotating blocks, in different locations of the barrier or with an inclined trajectory may be detrimental to the structure response but are not accounted for. The EAD-based assessment is thus, by definition, insufficient for estimating and quantifying the efficiency of barriers when exposed to impacts by real rock blocks in on-site conditions. This constitutes a potentially strong limitation in EAD-based barrier designs.

The use of flexible barriers in torrents for intercepting solid materials carried downstream by the flow (granular materials and tree trunks mainly) appeared in the early 2000's and

became more widespread over time. These structures are adapted from rockfall protection barriers and consist in slightly different arrangement of typically the same structural elements. The difference with the rockfall case concerns the loading applied on the barrier in terms of spatial distribution, duration and evolution with time. Barriers in torrents are exposed to loadings whose amplitude increases with time, over durations up to a few minutes and progressively applied on the whole net surface. Design recommendations have been proposed recently in Europe and Asia, mainly [Volkwein, 2014]. Due to limited knowledge on the barrier response and possible variety in flows to intercept, the loading cases considered in these documents remain rather simple. In addition, the proposed loading cases do not account for the interaction between the flow and the barrier, whose conformation changes with time, significantly influencing the loading in the various barrier components.

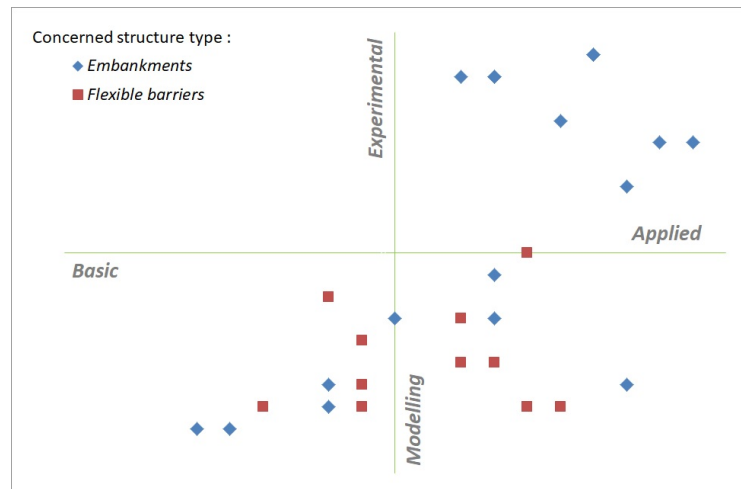
### **1.4 A contribution to the improvement of design practices**

My research is motivated by a profound attraction for mountains coupled to a strong will in improving protection against natural hazards in mountainous areas.

I graduated from the University Joseph Fourier in Grenoble (currently Univ. Grenoble Alpes) where I obtained a Msc in 1994. In 1996, I joined Cemagref (later renamed Irstea, then INRAe) to lead the geosynthetics testing lab in Antony (92). For five years I have been in charge of the team and lab technical management, while being involved in test methods standardisation (Fr and EU) and associated to product-related and prenormative research projects. In 2002, I took the opportunity I was given to move to Cemagref Grenoble and work on civil engineering structures designed to protect elements at risks against natural hazards in mountain areas. I first finalized the development of a numerical tool for designing torrent control dams (BARTO) before starting my PhD thesis in 2003, in parallel to that of D. Bertrand [Bertrand, 2006]. This opportunity to work on rockfall protection embankments was given to me by F. Nicot.

Over the last fifteen year, my research work has concerned some key obstacles associated with the design of rockfall protection embankments, flexible barriers and debris flows containment flexible barriers. My main research interests were, first, the characterization of the mechanical response of protective structures to dynamic loadings and, second, the evaluation of the effect of protective structures on gravity driven natural hazards.

My research is mainly oriented towards applied contributions, in view of providing end-users with new insights and methods. It is motivated by a strong will in enhancing knowledge on the mechanical response of embankments and flexible barriers, for contributing to the improvement of design methods while filling the gap between academic knowledge and engineering practices. In keeping with this posture, my contribution is positioned at the interface between basic and applied research. As a consequence, the deliverables of my research are aimed at both academics and practitioners. This is illustrated in Figure 1.3 showing the spectrum covered by the journal articles I was associated to, based on their content. Some articles are clearly aimed at engineers, providing them with applied research results, while



**Figure 1.3** Spectrum of my research work based on the content of the concerned peer-reviewed journal articles (listed in annex ??).

others rather constitute scientific inputs for academics. This figure also shows that most of my work is based on a synergy between experiments and modelling. Experimental works were conducted at various scales, from the constitutive materials to the structure scale. Modelling mainly concerned numerical simulations using a discrete element method (DEM).

The bulk of my work has been conducted through joint projects, with different sources of funding and involving various strong collaborations with researchers together with the contribution from doctoral fellows I co-supervised. These projects are listed below, from most to least important ones, in terms of number of journal articles in particular:

- **REMPARE:** *Ré-ingénierie des merlons pare-blocs par composants anthropiques recyclés*. Funded by ANR-PGCU. 2007-2010. 12 public and private partners. Collaborations with P. Villard and P. Gotteland (3SR, UGA), E. Haza (CER-Rouen), F. Bourrier and F. Nicot (INRAe), Géolithe and Razel. Doctoral thesis of A. Heymann (2009-2012).
- **C2ROP:** *Chutes de blocs, Risques Rocheux et Ouvrages de Protection*. National project. 44 public and private partners. Collaboration on rockfall protection embankments with P. Villard (3SR, UGA), Géolithe and Terre Armée. Collaboration on rockfall protection barriers with M.A. Chanut (Cerema) and F. Nicot (INRAe). Doctoral thesis of J. Coulibaly (2014-2017) and A. Furet (2017-2020).
- **Mumolade:** *Multiscale modelling of landslides and debris flows*. FP7, Marie Curie ITN. 2012-2015. Collaboration with B. Chareye (3SR, UGA) and F. Nicot (INRAe). Doctoral thesis of A. Albaba (2012-2015).
- **Pridyn:** *Protection contre les Risques naturels DYNamiques*. FUI Project, 2017-2023. Led by NGE Fondations. 5 private and public partners. Collaboration with F. Bourrier (INRAe).

- **AERES:** *Analysis of existing rockfall protection embankments of Switzerland.* Funded by OFEV (Bern, Ch). 2013-2017. Collaboration with B. Kister (HSLU, Switzerland).
- **DiMerl:** Part 1 : *Analyse technique du parc de merlons RTM* and Part 2 : *Risque résiduel à l'aval des merlons.* Funded by MEDDE-DGPR/SRNH in 2011 and 2013. Collaboration with F. Bourrier and D. Toe (INRAe).
- **Indyx:** *Interfaces dynamiques sol-géotextile.* Funded by RNVO-VOR in 2011 and 2013. Collaboration with P. Villard and O. Jenck (3SR, UGA) and I. Benessalah (Univ. of Chleff, Algeria).
- **Filtor:** *Intractions entre un barrage souple de type filet et écoulements torrentiels: focus sur les flottants.* Funded by MEDDE-DGPR/SRNH. 2019-2020. Collaboration with G. Piton and F. Bourrier (INRAe).

In addition to these funded projects, my research work also benefited from collaborations with J. Baroth (3SR, UGA), T. Faug (INRAe), L. Govoni, A. Mentani and G. Gottardi (DICAM, U. of Bologna, Italy) and from the doctoral thesis of L. Zhang (2012-2015) that I co-supervised with F. Nicot (INRAe).

## 1.5 Manuscript content

This manuscript presents a synthesis of most of this work, with the aim of illustrating its various facets in terms of approach, contribution nature, collaborations and goals, while considering the different structure types concerned. Main focus is placed on works that have led to results with added value for practitioners. More basic research works are not treated. For instance, the DEM study of the impact response of a granular layer conducted with L. Zhang during her thesis is not addressed [Zhang et al., 2017a,b], neither than the comparison of discrete element simulation results with the shock wave solution proposed by T. Faug for the case of a dry granular flow impacting a wall [Albaba et al., 2018]. Also, ongoing works aiming at producing results of interest for end-users are not detailed but are considered as outlooks. This in particular concerns the thesis work conducted by A. Furet, that I co-supervised with P. Villard (3R).

The manuscript is structured as follows.

First, chapter 2 deals with rockfall protection embankments, and more specifically with sandwich RPEs. This innovative type of protection structure aims at proposing a new structure design with demonstrated energy dissipative capacities. This chapter puts emphasis on the multi-scale approach adopted for the experiments, as well as on the interaction between the experimental works and the numerical developments.

Chapter 3 presents the numerical models developed for flexible barriers aiming at intercepting rockfall and those aiming at containing debris flows. In this chapter, a particular

## CHAPTER 1. PROTECTION AGAINST GRAVITY-DRIVEN NATURAL HAZARDS IN MOUNTAIN AREAS

---

attention is placed on the model calibration and validation with the aim of demonstrating the capacities of these models in mimicking the structures response so that, in the end, these models are used in a predictive manner for design improvement purpose.

Chapter 4 focuses on the assessment of the efficiency of rockfall protection embankments and flexible barriers. The proposed approaches were developed based in particular on the works presented in the previous chapters with the aim of providing end-users with tools to be used for evaluating the efficiency of protective structures in real contexts.

Finally, chapter 5 introduces two ongoing projects, mentioning the tackled key questions and presenting some results.



## Chapter 2

# Towards an advanced design of rockfall protection embankments

### 2.1 Introduction

#### 2.1.1 Motivations

Methods available to engineers for designing RPEs with respect to impact are globally deficient (see section 1.3.2). In their classical design, the efficiency of RPEs in resisting the impact implicitly results from the volume of material involved in the structure impact response. The main development during the last four decades concerned the use of reinforcement elements (geosynthetic) for improving the design of RPEs. Very limited focus was placed on the influence of the characteristics of the fills on the RPEs impact strength.

In such a context, responding the demand for RPEs with reduced footprint requires proposing innovative designs. This optimization may in particular rely on the improvement of the structure constitutive materials capacity in dissipating the impact energy. In this aim, RPEs consisting in sandwich structures have been developed within the framework of the REMPARe project that started after the completion of two PhD thesis [Bertrand, 2006; Lambert, 2007]. This project aimed at proposing an improved and eco-friendly type of rockfall protection embankment with reduced foot-print.

#### 2.1.2 Sandwich RPEs

Sandwich RPEs are innovative structures consisting in interconnected gabion cages forming vertical-sided and layered-walls to be exposed to rockfall impact. The sandwich nature results from the use of different fills, with specific properties, from one vertical layer to the other. These sandwich structures may consist of two or three vertical layers of gabions and be either designed to be free-standing or laid against a ground compacted earth mound. On a technological view point, the aim is to improve the capacity in dissipating the impact energy, by favouring plastic deformation of easily accessible, and thus easy to repair, gabion cells. In

the framework of the REMPARe project, crushed quarry limestone, end-of-life tires mixed with sand and ballast recycled from railway tracks were considered as fill.

Various issues were addressed by the consortium. In complement to the study of the mechanical response of sandwich RPEs, that is presented in the following, issues related to the environmental impact and fire risk were also addressed and revealed that the use of end-of-life tires had no significant adverse effect to the environment except in case of fire [Hennebert et al., 2014].

A multi-scale mechanical characterisation under both static and dynamic loadings was conducted, from the constitutive materials to the structure scales. Experiments at the gabion scale were part of my PhD thesis and are not treated in the following [Lambert, 2007]. The obtained results ([Lambert et al., 2009]) were in particular used for calibrating and validating the numerical models of gabion cells and RPEs developed by D. Bertrand, F. Bourrier and A. Breugnot [Bertrand et al., 2005, 2006; Bourrier et al., 2011; Breugnot et al., 2016]. Experiments on half- and real-scale structures were conducted during the PhD thesis of A. Heymann, co-supervised by P. Gotteland, F. Nicot and myself [Heymann, 2012]. Overall, the major achievement of this project remains in the impact experiments conducted on three real-scale structures with embedded instrumentation [Lambert et al., 2014, 2019].

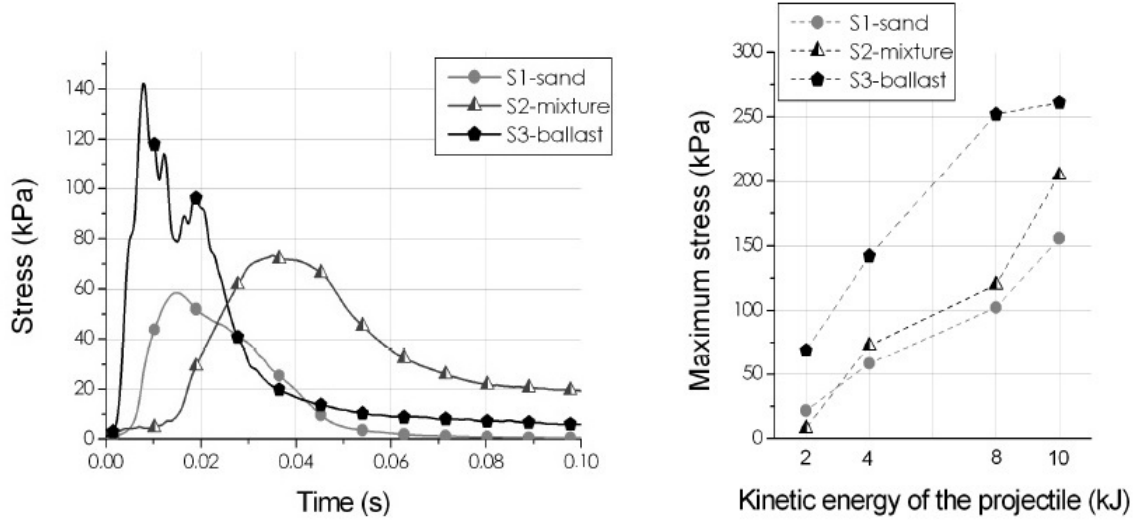
This work is illustrated in the following, presenting results from impact experiments on half- and real-scale structures.

## 2.2 Half-scale structure impact response

On the basis of experiments at the cell scale and before conducting experiments at the real scale, half-scale experiments were conducted on three two-layered sandwich structures leaned against a rigid wall. In this purpose 0.5m in size cubic cells were used to form structures 1.5 m in height, 2.5 m in length and 1 m in width. The three tested structures differed in the fill of the second layer: sand, mixture of 30% by mass of scrapped tire with sand (STM). The front layer was filled with crushed quarry limestone. Four successive normal-to-the-face impacts were carried out increasing the impact energy (2, 4, 8 and 10 kJ). A fifth test was conducted repeating the last impact.

These experiments in particular aimed at evaluating the influence of the second layer fill characteristics on the structure response in terms of stress transmitted to the rigid wall, in particular. On one side, ballast was expected to increase the structure inertia, due its higher unit mass, while being stiffer. On the other, the sand-tire mixture was expected to favour energy dissipation by allowing large strain while permitting a certain structure geometry recovery after impact, due to its elasticity [Lambert et al., 2009]. These two materials were thus expected to give sandwich structures different global characteristics when used as second layer fill.

These experiments also gave the opportunity to test different techniques for measuring the acceleration within the structure and in particular in coarse materials [Heymann, 2012].

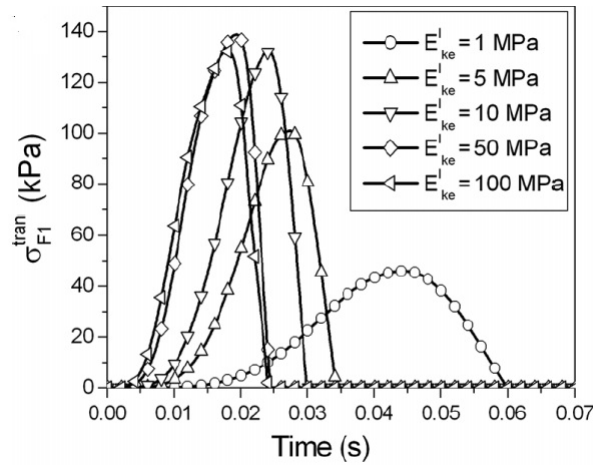


**Figure 2.1** Stress measured on the wall in the impact direction: time evolution recorded during the 4-kJ impact test (left) and evolution of the peak values during the tests series (right). [Heymann et al., 2010a]

The comparison between the three structures shows that ballast is the less efficient second layer fill for reducing the stress peak transmitted to the rigid wall (Fig. 2.1). Sand is slightly more efficient than the sand-tyre mixture. Simulations based on the model described in Bourrier et al. [2011] confirmed that increasing the fill loading modulus leads to a reduction in the impact duration and an increase in the transmitted stress peak value (Fig. 2.2). Both these trends are globally in accordance with those observed Figure 2.1, left.

The higher modulus of ballast, resulting from its low sensitivity to compaction, has consequences on the structure deformation. Indeed, ballast results in an higher contribution of the front layer to the structure width reduction (Fig. 2.3). From the very first test, the structure width reduction in the impact axis concentrates in the front layer mainly, compared to the two other structures where the second layer contributes to 30% approximately to the structure width reduction. Width reduction of the front layer is higher with ballast, for instance reaching 200mm after test 3 compared to 150 and 140mm for the two other structures. This is in line with the higher crushing observed at the front face compared to other structures suggesting more stone crushing in the former case.

Other general trends were derived from the measurements made during all the experiments, based on the peak values. For example, the use of mixture tends to favour lateral stress diffusion [Heymann, 2012]. On the opposite, a slightly higher stress concentration in the impact direction is observed when using ballast as second layer fill. The repetition of impacts has consequence on the structures response during the test series as a result of impact-induced crushing, compaction and front face deformation [Heymann, 2012; Heymann et al., 2010b,a]. The amplitude of these phenomena depends on the characteristics of the



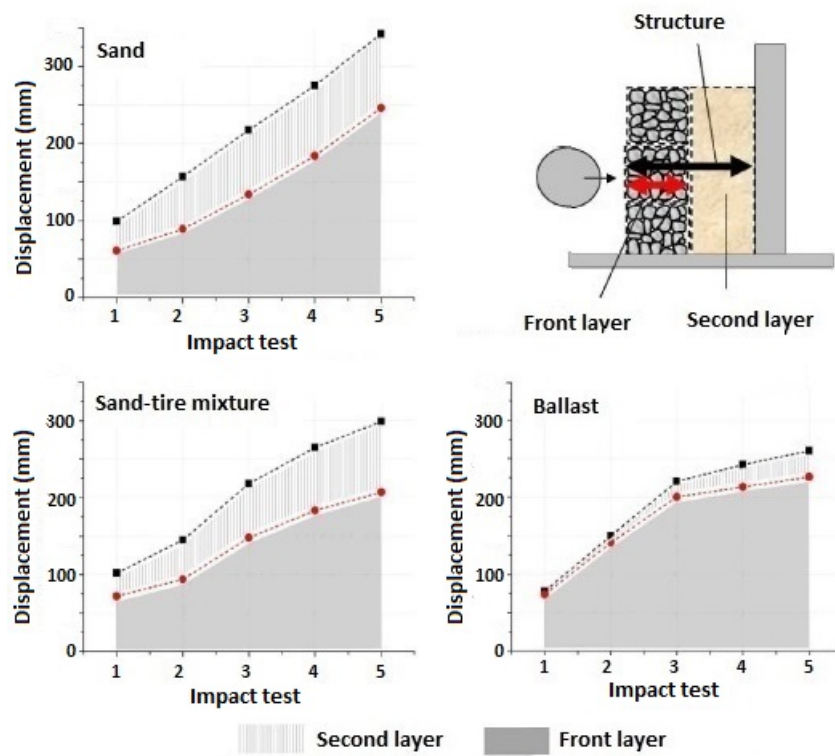
**Figure 2.2** Simulation results showing the influence of the fill material modulus ( $E_{ke}^i$ ) on the stress on the wall in the impact axis direction for a 4-kJ impact. [Bourrier et al., 2011]

second layer fill characteristics. The increase in stress on the wall is almost linear when using the mixture as second layer fill. This is attributed to the presence of pieces of tires in the fill. By contrast, when using sand as second layer fill, the evolution of the stress on the wall is strongly non-linear. This trend is associated to sand progressive compaction.

The first practical conclusion from these experiments is that sand is the most efficient as second layer fill for reducing the impact load on a rigid wall. The difference with the sand-tyre mixture is little. This is consistent with conclusions drawn from impacts on single cells. The second conclusion of practical interest is that using ballast favours stone crushing in the first layer while increasing the loading on the wall. The higher modulus of ballast leads to a higher stone crushing in the front layer and also explains the difference in terms of stress on the wall compared to the other fills. Both the curve shape and peak values are attributed to the modulus of ballast, giving the second layer a solid-body-like behaviour. The difference in unit mass of the different fills is thought to be less influential because the structure displacement is limited by the rigid wall.

## 2.3 Real-scale structure impact response

The impact response of real-scale sandwich structures was investigated considering 3 structures differing in their design. These structures were 4m in height and 8m in length and built using 1m in size cubic cells. Gabions at the faces were filled with crushed quarry limestone. The first structure consisted in a two-layered sandwich structure leaned against a ground compacted earth mound (Fig. 2.4, left). The second layer was filled with a mixture of 30% by mass of scrapped tyres with sand. The two other structures consisted in three-layered free-standing sandwich structures, differing in their middle layer fill: sand-tire mixture or ballast (Fig. 2.4, right).



**Figure 2.3** Cumulative post-impact deformation in the impact direction axis of the three structures, displaying the contribution of the front and second layers. [Heymann, 2012]



**Figure 2.4** First and second type of real-scale structures, before impact (left and right, resp).

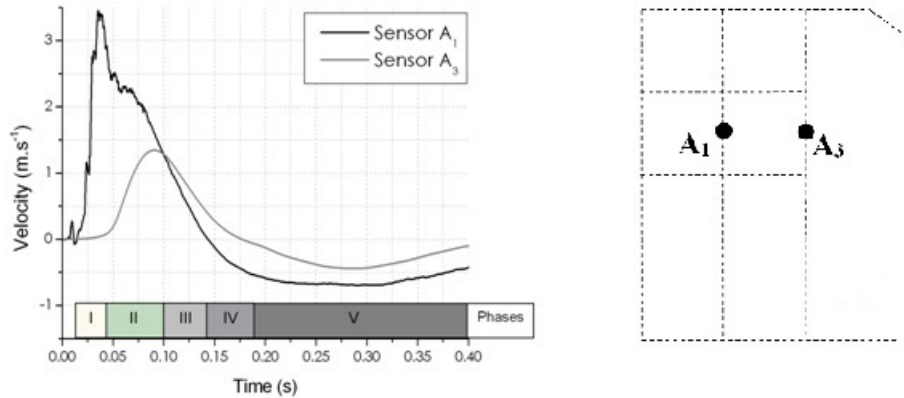
Each of these three structures was impacted successively, increasing the kinetic energy from 200 to 2200 kJ. The projectile was a 1.6 m in diameter and 6500 kg in mass sphere hanged to a cable way. It impacted the structure at mid-height approximately with a trajectory inclination in the 18-28° range.

These experimental rockfall protection embankment were instrumented to an extent never seen before. Measurements concerned: (i) the projectile kinematics, (ii) the acceleration and displacement of different points within the structure, (iii) the structure geometry change after each impact and (iv) the change in fill density after each impact. The different tools and techniques used in this purpose were: a high speed camera, accelerometers, linear position transducers, inclinometers, topography and tomography. Partial redundancy between these techniques aimed at allowing a cross comparison of the measurements for validation purpose.

Repair works were conducted when large deformation or damage were observed, in order to restore the structure characteristics. Two repair techniques were employed in this purpose depending on the observed damage level [Lambert et al., 2014].

### 2.3.1 Sandwich structure as embankment facing

When exposed to a 210-kJ energy impact, the sandwich structure leaned against an earth mound (Fig. 2.4, left), experiences different phases in terms of deformation in the impact plane. The velocity derived from the acceleration measured on both sides of the second layer globally reveals a time lag and an amplitude reduction from one point to the other (Fig. 2.5). Five different phases can be distinguished. Phase I corresponds to a compression phase of the second layer. It lasts from 20 to 40 ms. During this phase, the first interface (i.e. sensor A1) experiences a rapid acceleration, while the second interface is motionless (i.e. A3). Phase II starts from the time the second interface begins moving ( $t=40\text{ms}$ ). From this time, the second layer is shifted progressively in the impact direction. Compression still develops as long as the velocity at the first interface is higher than that at the second interface. The second layer width reduction reaches a maximum value of 120 mm at the end of this phase



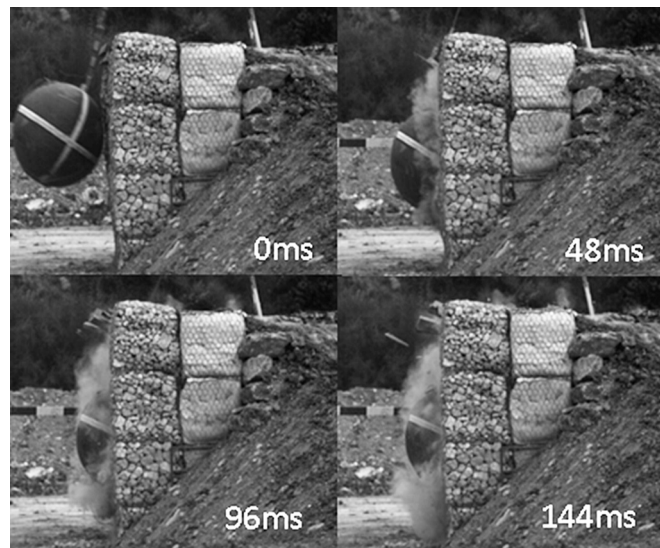
**Figure 2.5** Velocity in the impact direction, measured at two points located on the opposite sides of the middle layer and 2.5m from the ground. [Lambert et al., 2014]

(100 ms). During the next phase (III, 100-145 ms), both velocities decrease but the difference in interface velocities reveals a progressive expansion of the second layer. This expansion lasts till the structure is at rest. During phase IV (145-175 ms), the two interfaces move in opposite directions. During the last phase (V) both velocities are negative, revealing a global second layer displacement in the direction opposite the impact direction. As a result of its expansion, the second layer final width slightly exceeds its initial value. This results from the elasticity of the second layer fill material allowing this layer to restore its initial dimensions after impact. This design is thus advantageous in terms of post impact repair as damage mainly concentrates in the first layer.

During the 2200-kJ impact, the structure experienced large deformation without reaching failure nor collapse (Fig. 2.6). The maximal projectile penetration exceeded 800mm. Significant post-impact changes in the geometrical and mechanical characteristics of both the sandwich structure and the earth mound were observed (Fig. 2.7). This latter exhibited cracks, compaction and bulking. Generalised crushing was observed in the impacted area through the first layer. In the aside plane, tilting and settling of the sandwich structure were also observed.

All these observations provide original insights concerning the impact response of these structures. Crushing of the coarse materials comprising the front facing layer dissipates energy and attenuates the stress on the second layer. The sand-tyre mixture exhibits elasticity that allows the second layer to restore its dimensions after impact. The wire netting distributes the load within the structure, while facilitating the structure post-impact repair.

In parallel, the collected data were used for validating the numerical model presented by Breugnot et al. [2016]. The originality in the modelling approach lies in the coupling between the discrete element method in the impacted area, and the finite difference method far away. Once validated, this model was used for addressing the influence of parameters such as the projectile shape and impact height on the projectile penetration and impact force for a 500-kJ



**Figure 2.6** High-speed camera images during the 2200-kJ impact on the embankment with a sandwich structure facing. [Lambert et al., 2014]

impact energy (Fig. 2.8). These simulation results clearly show that the sole projectile kinetic energy is not sufficient for estimating the block-structure interaction, and consequently the global embankment response to impact.

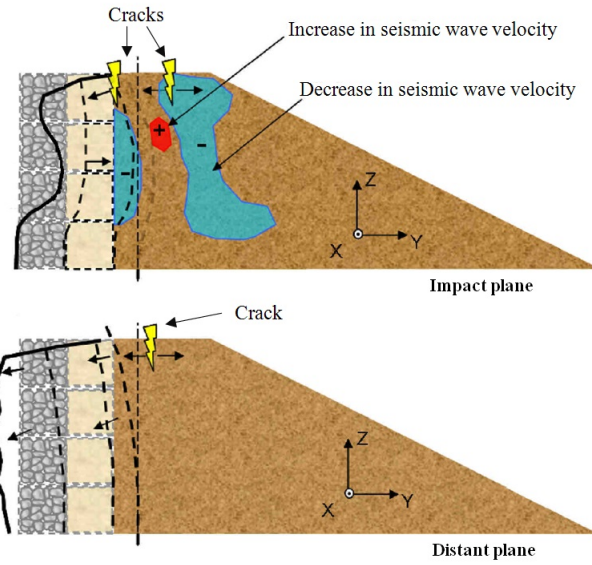
### 2.3.2 Free-standing sandwich structures

By contrast with the previous one, this type of structure differs by the boundary conditions at the back face and by the number of layers. The middle fill layer of the two free-standing structures were either ballast or the sand-tyre mixture (referred to as structures BA and STM respectively).

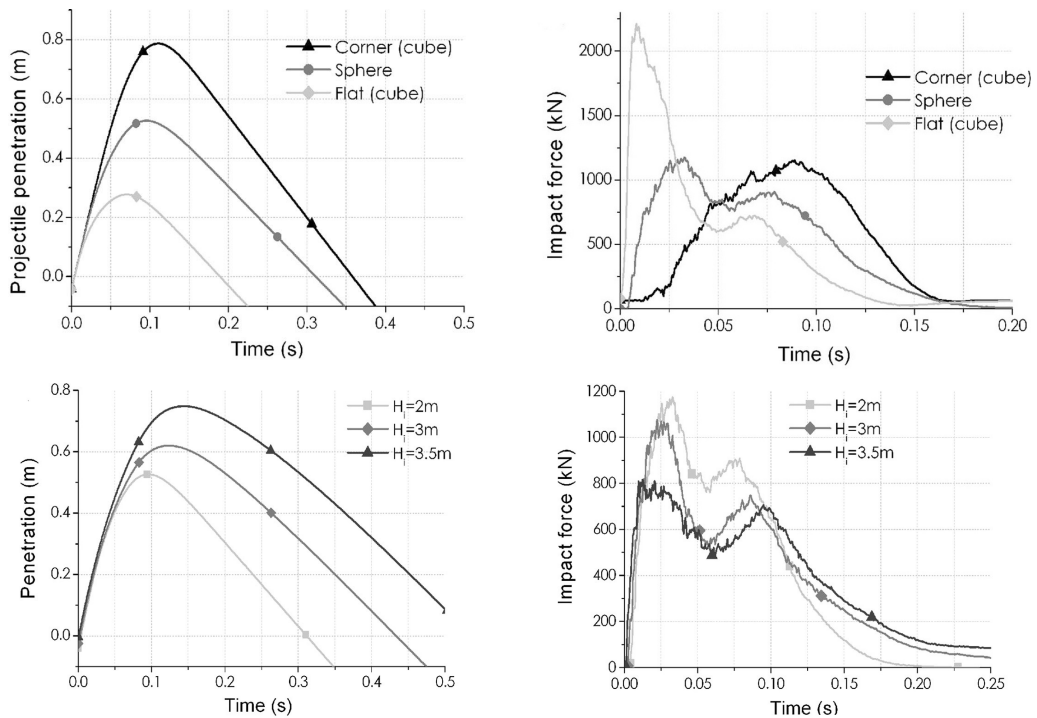
The difference in middle layer fill had almost no influence on the impact force but had a significant influence on the structure global deformation from the first impact test (Fig. 2.9)[Lambert et al., 2019]. At the end of the test series, structure STM experienced larger settlement (0.35 vs. 0.2m) and back face displacement (0.9 vs. 0.7m). This latter parameter is considered as highly relevant for comparing the response of narrow and free-standing structures as it relates to their post-impact stability and to the additional space required for their normal operation.

The difference in middle layer fill had an higher influence of the mechanisms at work in the different layers during the impact, as revealed by the layers width evolution during the second impact that involved an impact energy of 500kJ (Fig. 2.10). When ballast is used as fill, the first layer width variation is much higher than that when using the sand-tyre mixture. The whole structure width variation concentrates on the first layer with ballast while it is more equally distributed between the first and second layers for structure STM. Also, the middle layer experienced higher width recovery when filled with the sand-tyre mixture. In

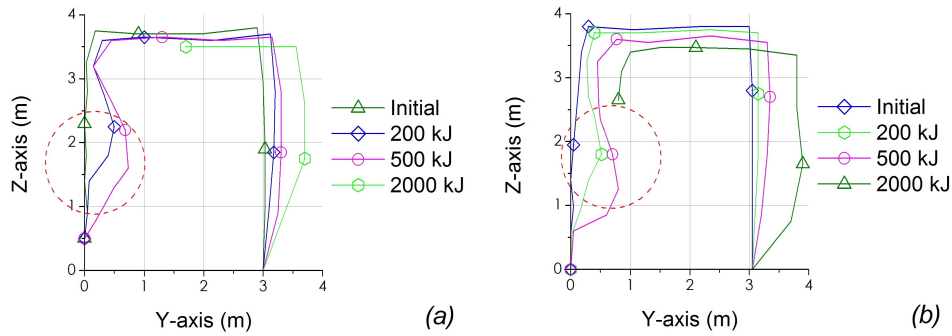




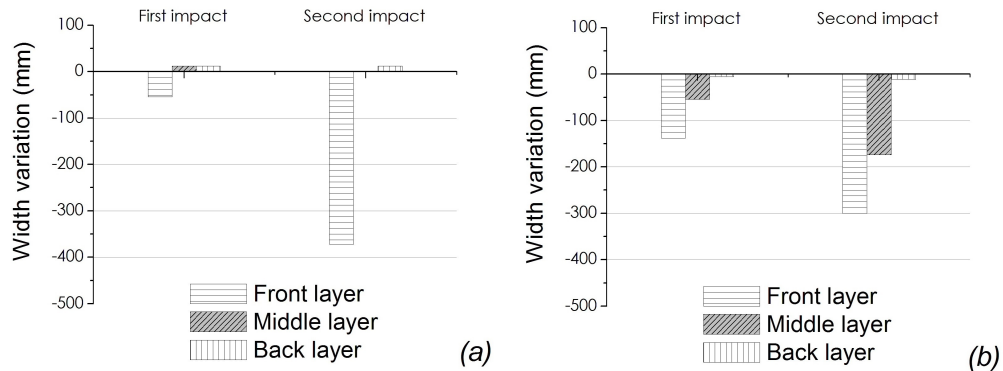
**Figure 2.7** Vertical cross-section of the structure showing the impact induced changes after the impact series, in the impact direction and 2m aside (up and down, resp.) [Lambert et al., 2014].



**Figure 2.8** Projectile penetration and impact force for different projectile tips and impact height (top and bottom, resp.). Simulations at a 500-kJ impact energy from [Breugnot et al., 2016]



**Figure 2.9** Evolution of the cross-section of free-standing structures BA (a) and STM (b) during the test campaign. The position of the projectile while at rest after the third impact is also shown. [Lambert et al., 2019]



**Figure 2.10** Cumulative evolution of the residual width of each layer of structure BA (a) and structure STM (b), at 1.5 from the ground. [Lambert et al., 2019]

the end, the conclusion is that ballast used as second fill results in higher crushing in the first layer.

The comparison between the two structures reveals that ballast used as middle fill improves the structure impact response. This is attributed to the higher unit mass and shear strength of this material, both increasing the apparent modulus at the interface between the first and middle layers, resulting in a higher crushing in the first layer and in the increase in the mass associated with the structure response.

## 2.4 Synthesis

This chapter has presented a multi-scale approach for addressing the impact response of cellular sandwich RPEs. The collected data gives a truly original description of the response of RPEs to impact. The various experiments provide a valuable set of data for characterizing

the impact response of gabion structures, for example in view of developing numerical models.

The influence of the gabion fill characteristics on the structure response has been highlighted at both the half-scale and the real-scale. Experiments at the real-scale revealed that slender free-standing RPEs, 3-m in width, are efficient for arresting projectiles with a 2000-kJ kinetic energy while experiencing limited back face deformation. Ballast is proved to be the optimum fill for the middle layer for a three-layered structure.

This work also illustrates the interest of a multi-scale approach, in particular when combining experiments with numerical modelling. The experiments at the gabion scale contributed to the interpretation of the structure impact response and, in parallel, were used for calibrating numerical models of gabion cell that were further considered for simulating the structure impact response. The developed models were in particular used for addressing the influence of some parameters related to fill characteristics, for confirming assumptions made based on experimental results and, in an exploratory process, related to the influence of the impact conditions .

CHAPTER 2. TOWARDS AN ADVANCED DESIGN OF ROCKFALL PROTECTION  
EMBANKMENTS

---

## Chapter 3

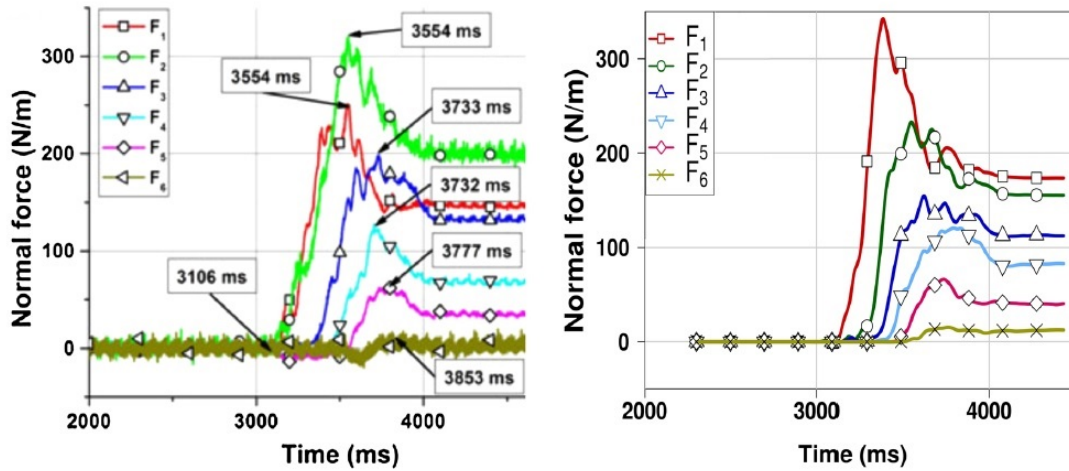
# Modelling flexible barriers for design improvement purpose

### 3.1 Introduction

Numerical modelling appears particularly relevant for addressing the complex dynamic response of flexible barriers due to the intricacy and diversity of commercially available structures (see section 1.2.2). The very first use of numerical tools for modelling the response of flexible barriers concerned impact by a rockfall and dates back to the early 90's. A very large number of models have been proposed worldwide since then, and in particular over the last five years due to the significant improvement of computation methods and tools. The vast majority of these models were calibrated from experiments on real structures, including conformance tests prescribed by the EAD [EOTA, 2018]. In parallel, numerical models have been progressively used for modelling debris flow catchment barriers. The models efficiency in accurately simulating the barrier dynamic response has considerably increased over the past few years. Their predictive capacity has now reached a level of reliability allowing for their use as design improvement tools. The use of these models may benefit to both the manufacturers and the natural hazard technical consultants.

Within the framework of different collaborations we contributed to this dynamic, developing models for both rockfall and debris flow protection barriers. These models were developed based on a discrete element method (DEM). DEM offers the possibility to model the various components of the investigated systems (barrier components, rock block, granular flow) in a same environment, allowing accounting for their peculiarities in terms of geometrical and mechanical characteristics, while naturally allowing large displacement and strain to develop.

These models are presented in the following emphasizing their potential for improving design practices and methods, for both rockfall protection and debris flow containment. In this aim, the modelling approaches are described and the main results are presented and discussed.



**Figure 3.1** Validation of the flowing material model. Impact force values at different heights on the rigid wall ( $F_1$  at the toe to  $F_6$  at the top). Numerical vs. experimental results from Jiang and Towhata [2013](right and left resp.). [Albaba et al., 2015]

## 3.2 Debris flows catchment barrier

### 3.2.1 Context

This work was part of the MUMOLADE project (FP7, Marie Curie ITN) and was carried out by A. Albaba during his PhD thesis (2012-2015) and under the supervision of F. Nicot (INRAe), B. Chareyre (3SR) and I.

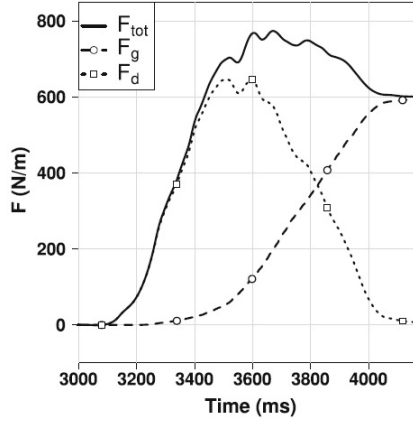
The model was developed with YADE software [Smilauer et al., 2014] paying a particular attention to the modelling of the granular flow, based on experimental data from the literature. A dry granular flowing material and a generic barrier were considered.

This work was conducted in the aim of better understanding the response of such flexible barriers when impacted by a granular flow considered representative of coarse debris flows, in view of contributing to the improvement of their design.

### 3.2.2 Flow model

The flowing material model was developed considering the case of an inclined flume with different inclination angles and closed by a rigid wall [Jiang and Towhata, 2013]. The modelled dry granular flow was composed of poly-dispersed non-spherical clumps of particles.

A visco-elastic contact law with Mohr-Coulomb failure criterion was adopted for the inter-particles contact. The model calibration was carried out based on the flow thickness and velocity and on the final shape of the deposit behind the wall [Albaba et al., 2015]. Quantitative comparison with experimental data showed very good agreement in terms of the peak impact force on the wall, the time to the peak and the residual force (Fig. 3.1).



**Figure 3.2** Force acting on the wall: total ( $F_{tot}$ ), dynamic component ( $F_d$ ) and static component ( $F_g$ ). [Albaba et al., 2015]

At the wall scale, the simulations allowed tracking the evolution with time of the total force as well as the static component, due to the mass of the dead zone, and the dynamic component, resulting from the flowing particles (Fig. 3.2). The dynamic component was found to contribute to 85% of the maximum total impact force on the wall indicating that the peak force is reached before a significant amount of dead particles accumulates behind the wall.

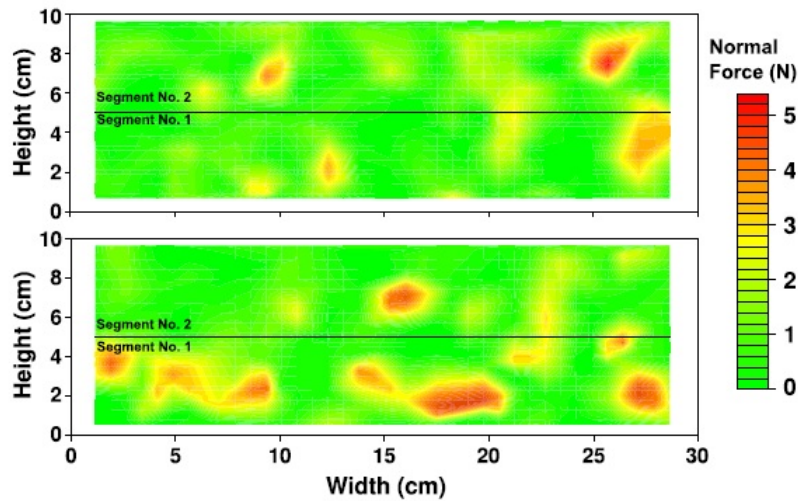
Locally, the load on the wall exhibited significant variability from one simulation to another as well as spatial heterogeneities (Fig. 3.3). This latter indicates the presence of arching effects in the granular medium behind the wall.

The developed model has shown capabilities of capturing the main features associated with the interaction between a dry granular flow and a rigid wall, in particular resulting in good predictions of the peak force along the height of the wall, the time to the peak and the residual force at the end of the process.

### 3.2.3 Barrier model

The modelling approach was applied to a generic barrier considered as representative of existing ones. It consisted of a net made of 45° rotated cable meshes, sliding rings, horizontal main cables, lateral cables, energy dissipating devices [Albaba et al., 2017].

In an innovative manner in the field of DEM, cables were modelled as continuous bodies, allowing naturally accounting for both the sliding of rings along supporting cables and the interaction between the granular flow and the net cables. The net element model was calibrated against net punching test data. The sliding rings were modelled as hollowed squares made of four cylinders that could slide along the main cables (Fig. 3.4). The value of the friction angle between sliding rings and main cables was calibrated using data from a specific zip-line



**Figure 3.3** The granular deposit at rest exerts a variable and heterogeneous loading on the rigid wall (Normal force at the end of two simulations in the same flow conditions). [Albaba et al., 2015]

full-scale experiment. Energy dissipating devices were modelled as elastic perfectly-plastic elements with threshold elastic limit and maximum allowable deformation.

### 3.2.4 Structure response

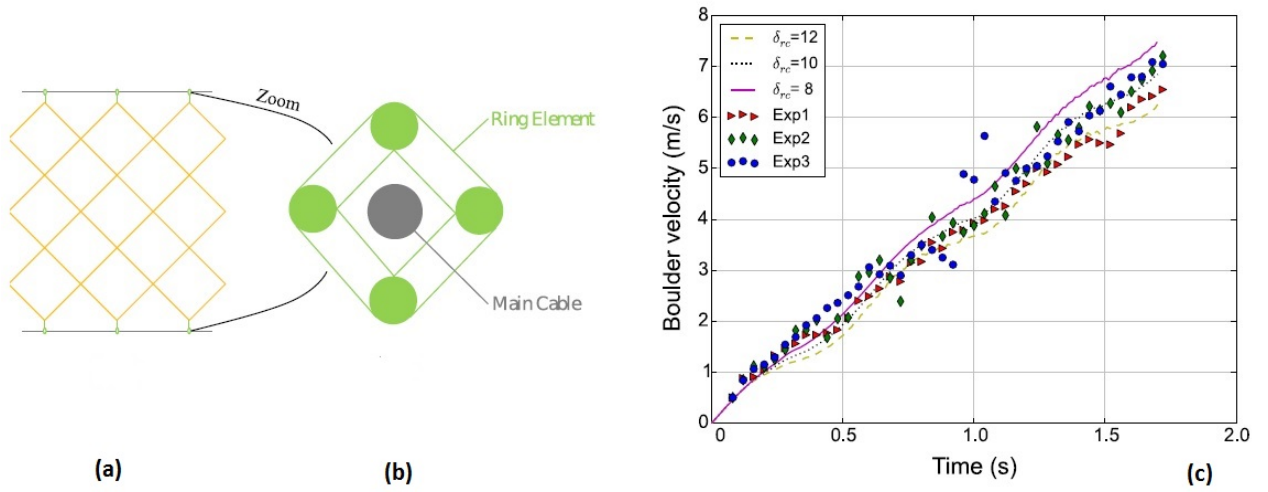
The two models were assembled to simulate the interception of a granular flow by a flexible barrier, 15.20 m in width and 5.5 m in height (Fig. 3.5). Two barriers were considered: with or without energy dissipating devices at the connection between each main cable extremity and fixed points representing the anchors.

Energy dissipating devices have a small influence on the flow dynamics, in terms of deposition rate, impact force on the structure and retaining capacity (Fig. 3.6). By contrast, the influence on the forces transmitted within the barrier is significant: energy dissipating devices lead to a reduction in a ratio of 3 of the forces in the main cables and in the anchors. By increasing the deformation of the structure, energy dissipating devices make it possible to significantly reduce internal forces. Also, energy dissipating devices resulted in a uniform force distribution from one main cable to the other (Fig. 3.7).

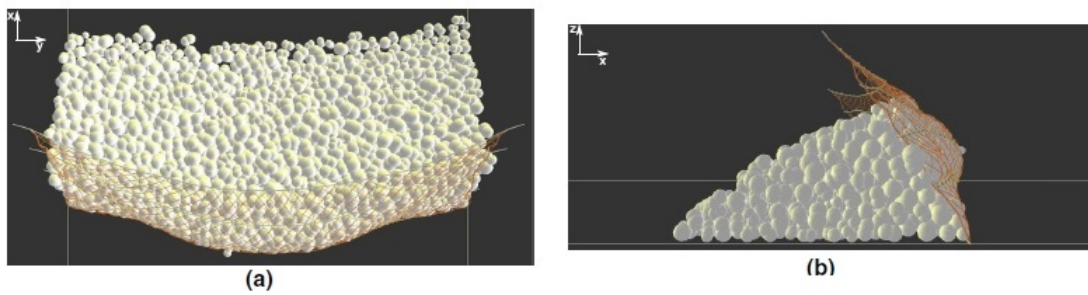
A sensitivity analysis revealed that changing the activation force of energy dissipating devices or impacting the barrier with successive small-sized surges lead to significant changes in the barrier response in terms of force development and its deformation mechanism.

The simulations have also shown that, surprisingly, very different global structure responses may be associated to very similar peak impact forces [Albaba et al., 2017]. This suggests that the design of any barrier may be based on a same estimate of the impact force related to the granular flow characteristics, and not to the structure response. By contrast,

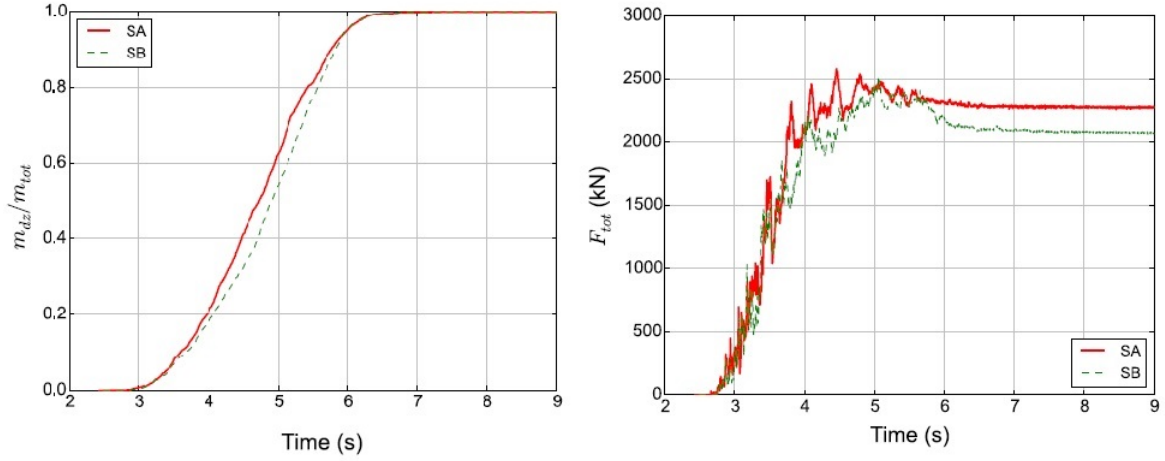




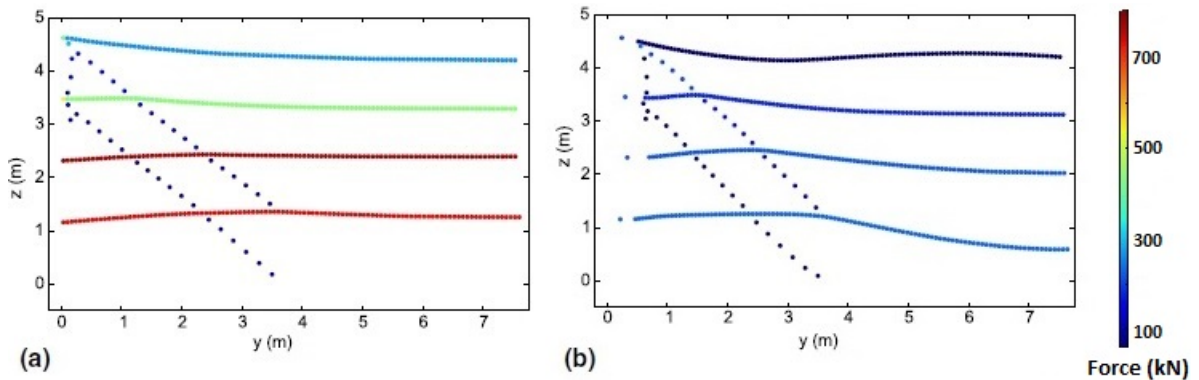
**Figure 3.4** Schematic representation of the modelled barrier (a), detail of the ring (b) and calibration of the cable-ring friction angle (c). [Albaba et al., 2017]



**Figure 3.5** Snapshots of the barrier at rest : top (a) and side (b) views. [Albaba et al., 2017]



**Figure 3.6** The total force applied by the flow on the barrier (right) and the dead zone mass (left) are marginally affected by the presence of energy dissipating devices at the extremities of the main cables (SB, SA : with and without dissipating device, resp.). [Albaba et al., 2017]



**Figure 3.7** The main cables are uniformly loaded in the presence of energy dissipating devices (b). Otherwise, very high tensile loads develop in these cables, with values up to 800 kN (a). [Albaba et al., 2017]

it puts emphasis on the correct modelling of the structure when exposed to this dynamic loading, in view of computing the loads in the various components of the structure.

### 3.2.5 Conclusion

A DEM model was developed in view of addressing the interaction between a granular flow and a flexible barrier. This model appears to be an effective tool for investigating the barrier response varying the structure design or granular flow characteristics.

The simulations have in particular shown that energy dissipating devices make it possible to significantly reduce internal forces by increasing the deformation of the structure. This has beneficial consequences as it limits the forces transmitted to the anchors, that are key components of these structures.

These conclusions were drawn considering a dry granular flow and a generic barrier. As a continuation of this work, more realistic structures and flowing materials are considered within the framework of the ongoing Pridyn project.

## 3.3 Rockfall protection barriers

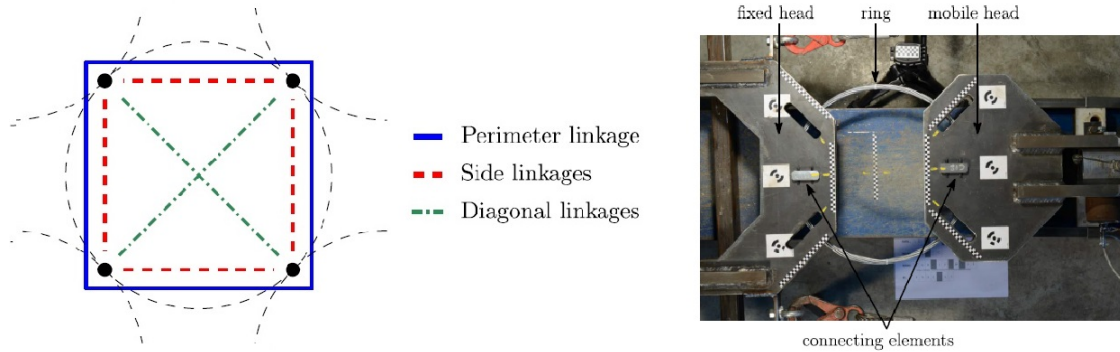
### 3.3.1 Context

Rockfall protection barriers are very complex structures (Fig. 1.2.2) whose efficient modelling during impact requires full consideration of the mechanical features of all their components and of the interaction between themselves. Indeed, upon impact, barriers exhibit a complex, non-linear, dynamic behaviour. Flexibility of the barrier leads to large displacements and changes in its conformation while irreversible mechanisms generate localized material non-linearities. This constitutes the general context in which a numerical model of rockfall protection barriers was developed as part of a productive collaboration with Cerema, whose aim is to provide a generic computational environment (GENEROCK software) dedicated to the modelling of the dynamic response of any type of barrier [Coulibaly et al., 2019].

The barrier model was developed by J. Coulibaly during his PhD thesis, co-supervised by F. Nicot (INRAe), M.-A Chanut (Cerema) and I. This work placed a particular emphasis on two features with major influence on the barrier impact response and requiring a sound mechanical investigation: the modelling of interception nets made from circular rings and the modelling of the so-called curtain effect that results from the sliding of the net along supporting cables.

### 3.3.2 Improved ring model

The most commonly used type of interception structure consists in a net made from large assemblies of interlaced steel rings. Their modelling requires a non-linear and computationally efficient mechanical model. An innovative discrete model of steel rings was developed,



**Figure 3.8** The ring model (left) was calibrated and validated based on tensile tests on single rings considering different testing conditions and rings (right).[Coulibaly et al., 2017]

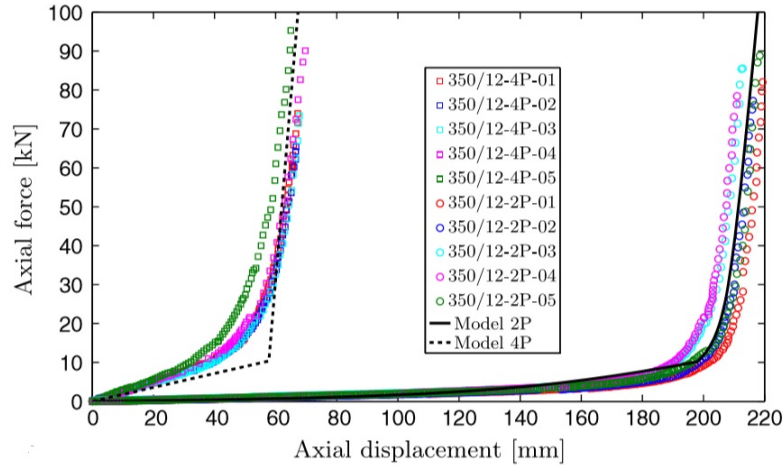
providing an effective mechanical response of the net at both the ring scale and the net scale [Coulibaly et al., 2017]. This model describes the ring as a collection of four nodes interacting one with each other through three interaction law types (Fig. 3.8, left). All these laws were given an elasto-plastic constitutive relation. Diagonal and side linkages work in compression while the perimeter linkage works in tension only. This innovative modelling approach allows accounting for most physical phenomena governing the ring mechanical response, when used in a flexible barrier.

The analytical model of the ring was established considering 2-point and 4-point traction loading configurations. The 14 parameters of the ring model were calibrated based on 2-point tensile tests on different rings, also considering an unloading phase (Fig. 3.8, right). Comparison with the experimental results from the 4-point traction has validated the model capacity to replicate the nonlinear behaviour of different rings (Fig. 3.9). The predicted axial force, as well as ring transverse deformation, show a good agreement with the experiments, in both the bending and tensile regimes, respectively observed for the low and large deformation ranges.

In the end, the formulation of the model makes it more complete than previously existing discrete ring models, and computationally inexpensive compared with more exact models while showing good results. These features make the proposed model particularly suitable for numerical simulation of large ring net assemblies where plastic deformation is often observed as a result of excessive penetration by the rock block. Provided the proposed testing protocol is followed, this model may be applied to any ring technology, with different sizes and mechanical characteristics.

### 3.3.3 Modelling of the curtain effect

The so-called curtain effect is a key mechanism in the barrier response as it controls most of the barrier deflection. This effect refers to the sliding along the barrier main cables of the interception net. The curtain effect favours structure deformation, resulting in lower



**Figure 3.9** Experimental and simulated axial force : the model was calibrated from 2-points tensile test results (with axial displacement up to 220 mm in this case) and validated for 4-points tensile tests (with axial displacement up to 70 mm in this case). [Coulibaly et al., 2017]

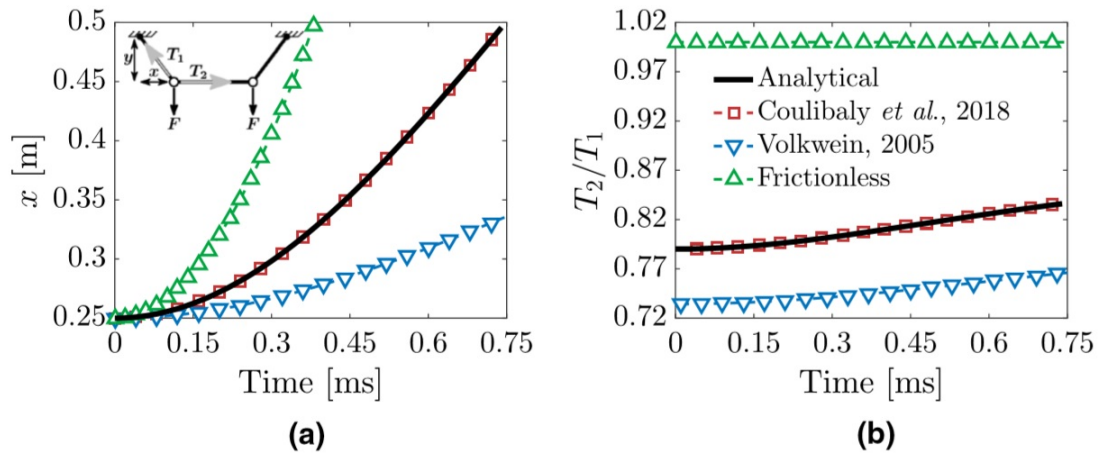
loads within the barrier. Sliding connections also concern the interaction between other components, as for instance the displacement of cables through posts in some structure types.

The developed model expands many previous works within a unique and compact formulation that allows effective modelling of complex non-linear dynamic systems involving sliding cables [Coulibaly et al., 2018]. It consists of a multi-node sliding cable accounting for friction, various cable material constitutive relations and for use in dynamic analyses. In an innovative way, the cable consists of sliding and non-sliding nodes. The sliding cable model as well as its numerical implementation were validated against a theoretical sliding cable mechanism. Simulation results agreed perfectly with the analytical solutions contrary to existing approaches (Fig. 3.10). Besides, comparison with existing sliding models simulating the curtain effect in rockfall barriers has exhibited the advantages of the proposed formulation over previous ones [Coulibaly et al., 2018]. It confirmed that discrepancies are observed whether or not friction is accounted for. It also revealed the importance of having the cable mass distributed on non-sliding nodes for correctly modelling the transient dynamic response. Indeed, the presence of these nodes ensures a regular mass distribution allowing reproducing inertia effects.

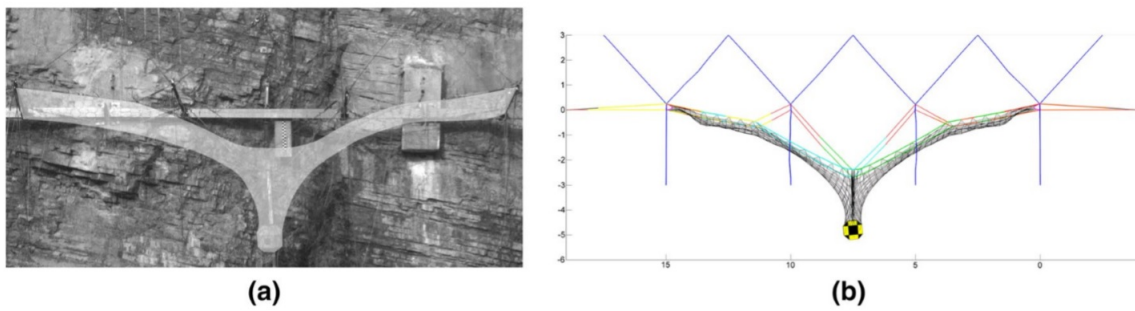
### 3.3.4 Model predictive capabilities

The motivation when developing numerical models of flexible barriers is to improve the design of these structures, by performing numerical experiments varying parameters related to the impact conditions or to the structure characteristics. This implies having reliable numerical tools with demonstrated predictive capacities.

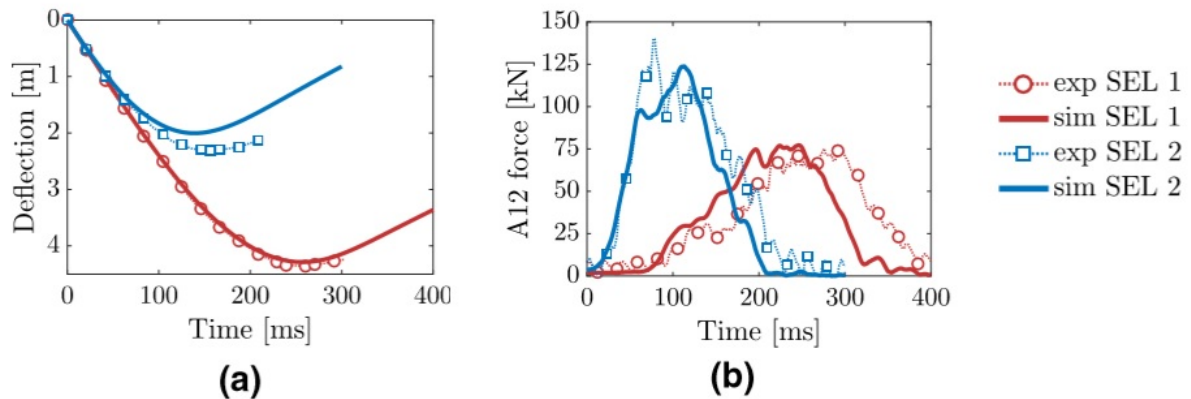
Two structures differing by their technology were considered for evaluating the potential of numerical modelling approaches making use of the previously presented models. This work



**Figure 3.10** Comparison of the proposed sliding node model with the analytical solution and existing approaches, in terms of displacement (a) and tension ratios around the sliding mass (b). [Coulibaly et al., 2018]



**Figure 3.11** Full-scale impact experiment (net highlighted for better visibility) and its simulation. [Coulibaly et al., 2019]



**Figure 3.12** Numerical vs. experimental results in case of successive impacts. Barrier deflection (a) and force in an anchor (b). [Coulibaly et al., 2019]

was conducted thanks to the GENEROCK software.

The two barrier models were validated by comparison with results from full-scale impact experiments conducted as part of the C2ROP project. These consisted in centred normal to the fence impacts repeated twice on the same structure (Fig. 3.11). For both structures, the modelling approach revealed satisfactory in predicting the structure response, on both quantitative and qualitative points of view, and considering the boulder displacement, forces in the main cables and forces acting within the various energy dissipating devices. It is particularly notable that this also concerned the case of successive impacts on the same structure (Fig. 3.12).

In the end, this comparison demonstrates the ability of the model in accounting for the non-linear and irreversible behaviour of ring nets and for the curtain effect. The developed models are well designed and their numerical implementation is effective, with a reduced computation cost, for addressing the complex non-linear behaviour of rockfall barriers.

The good predictive capacities of the models confirms that discrete element method is a well adapted numerical approach for modelling flexible rockfall barriers. It makes it possible to implement complex behaviour laws, including unloading phases, thanks to the explicit Lagrangian formulation of the method. These good predictive capacities also reveal the relevance of the calibration procedure based on quasi-static calibration of the different structural elements models, such as the energy dissipating devices.

### 3.4 Synthesis

Flexible barriers are rather large, thin and discontinuous structures whose response intricacy results from the use of various types of components, interconnected one with each other. During impact, strong material and geometrical non linearities develop with time, from the

loaded area to components further. Last, there is a very large diversity among existing structures, in terms of structure dimensions, mechanical and geometrical characteristics of components as well as number and lay out of these components within the barrier. The mechanical response of barriers to the dynamic loading that results from the interception of rockfall or debris flow is thus extremely hard to predict, making their design improvement complex and random. In this context, we contributed to the development of DEM models for such barriers.

As for debris barrier, this work provided insights concerning the interaction between a dry granular flow and the structure, on one side, and on the force distribution within the structure depending on the presence of dissipating devices, on the other. This work continues in the framework of the Pridyn project, focusing on a specific barrier and considering the effect of the fine matrix in the granular flow.

The key pillars in the work on rockfall barriers consisted, first, in an extensive use of experimental data for numerical model calibration and validation purposes. Specific experiments were conducted for investigating the mechanical response of single rings under tensile loading and the impact response of full-scale rockfall barriers. This latter type of tests allows validating the numerical models, which is a necessary prerequisite in view of using the model a predictive manner, for investigating the influence on the barrier mechanical response of various loading cases or of changes in the structure design [Coulibaly et al., 2019].

The second key pillar relates to the particular attention paid to some components and mechanisms with great influence on the barrier response, namely the ring net and the so-called curtain effect. In the first case, an advanced discrete model of steel rings accounting for most physical phenomena was developed. Comparison with the experimental results confirmed the model capacity to replicate the non-linear behaviour of different rings under different loading configurations. In the second case, an innovative approach was proposed and validated against an analytical solution for the sliding mechanism. Both these models are based on a sound mechanical approach and constitute significant advances with respect to existing ones.



## Chapter 4

# Assessing the efficiency of protection structures

### 4.1 Introduction

The final aim of any research related to civil engineering protective structures is to improve their efficiency in reducing the exposure of elements at risk. Failure in reducing the hazard may result from a lack in either the functional or the structural design, or both. For what concerns rockfall protection structures, this may be related to an insufficient interception height with respect to the block passing height or to an underestimation of the required structure impact strength.

We have addressed these two facets for rockfall protection embankments and flexible barriers, in the framework of different active collaborations. An expedient impact strength criterion was developed for RPEs and then applied to RPEs built in Switzerland and France in view of evaluating globally the efficiency of these collections. Still for RPEs, we have identified and solved problems related to the use of trajectory simulation codes in the presence of RPEs, in view of improving the modelling of the blocks propagation downhill the structure, allowing for a better quantification of the hazard reduction resulting from the construction of RPEs. For what concerns flexible barriers, we put a particular focus on the variability of design input parameters in relation to the rock block trajectories, for improving the design of barriers with respect to their ability in intercepting the blocks and resisting the associated impact loading.

The aim with these works is to provide design engineers with tools and key insights in view of contributing to a more efficient structure design. In this spirit, this chapter focuses on results with added value for practitioners, with less room given to the tools and methods employed.

## 4.2 Rockfall protection embankments

### 4.2.1 Impact strength assessment criterion

#### 4.2.1.1 Context

The work presented in the following section was accomplished during the DiMerl and AERES projects. The aim of this latter, conducted with B. Kister (HSLU, Switzerland) was fourfold. First, an inventory of the Swiss RPEs collection was conducted together with an enquiry on the current design practices. Second, an exhaustive state of the art was established [Lambert and Kister, 2017a]. The third aim was, based on this state of the art, to define an impact strength assessment criterion that was finally applied to the Swiss RPE collection [Lambert and Kister, 2017b]. Last, small scale experiments were conducted on RPEs with a rockery facing. This project was thus clearly oriented towards practitioners, with the goal of providing them with knowledge and tools to be used in operational contexts. The following section focuses on the impact strength assessment criterion, that is empirical and based on an exhaustive literature review.

The development of the impact strength assessment criterion was motivated by the realization that the vast majority of existing RPEs, in France and Switzerland in particular, were designed without any consideration for the dynamic loading [Lambert and Kister, 2017a].

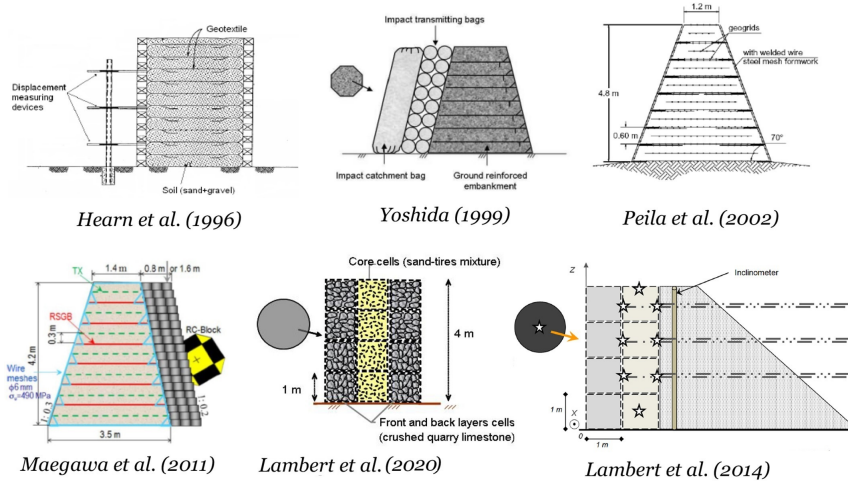
#### 4.2.1.2 Proposed criterion

Over the last decades, many studies have investigated the mechanical response of RPEs, based on experimental works at both small or real scales or based on numerical modelling (see an exhaustive review in [Lambert and Kister, 2017a]). Notably, 6 studies involved real-scale impact experiments on various types of structures (Fig. 4.1). These real-scale experiments constitute a trustworthy and indisputable source of data concerning the impact response of RPEs.

The concerned RPEs were all reinforced, had either a rectangular or a trapezoidal cross section, with a height ranging from 3 to 4.2m and a mid-height width ranging from 3 to 6.5m. In the results analysis, focus was placed on tests conducted in similar conditions. These were defined as a single rock block with a kinetic energy at impact ranging between 1 and 4.5MJ approximately and impacting the RPE close to its mid-height. The impact conditions are also defined by a 25-30% downward block incident trajectory, a block diameter typically half the structure height.

The barrier response is evaluated comparing the downhill face displacement to the incident block kinetic energy. The downhill face displacement reveals how close the structure is from collapse, that is to say when the rock block kinetic energy tends towards the structure capacity [Lambert and Bourrier, 2013].

In order to account for the differences in structure dimensions, both the downhill face displacement and the block kinetic energy are normalised. The downhill face displacement



**Figure 4.1** RPEs subjected for research purpose to real-scale impact experiments with kinetic energies higher than 1000 kJ (for the references, see [Lambert and Kister, 2018]).

is normalized by the mid-height width. This is motivated by the fact that, on one side, the selected experimental results concern tests with an impact point located at structure mid-height and that, on the other side, most of existing RPEs have a variable width, as having a trapezoidal cross-section. The block kinetic energy is normalised by the the cross-sectional area of the structure calculated from its toe to its crest. This area is considered as a proxy of the structure volume involved in its impact response.

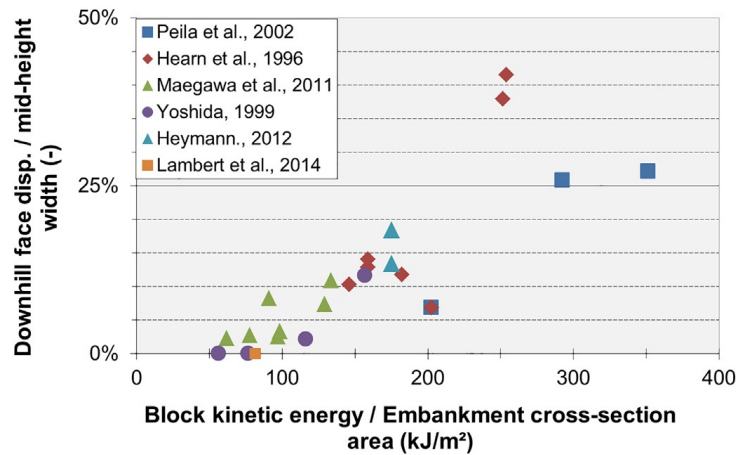
The results analysis clearly reveals that beyond a normalised kinetic energy of  $250 \text{ kJ/m}^2$  the downhill face displacement exceeds 25% the structure mid-height width (Fig. 4.2). Above this 25% threshold, the structure stability is critical, in particular in terms of post-impact stability. This value is also in line with threshold values in relation with analytical methods proposed in the literature (e.g.[Ronco et al., 2009]).

Fig. 4.2 thus allows proposing a criterion by which RPEs are deemed stable after impact, with a downhill face displacement less than 25% the structure width, if:

$$E'_{25} = \frac{KE}{250 * A} < 1 \quad (4.1)$$

where  $KE$  is the rock block incident kinetic energy (kJ),  $A$  is the structure cross-section area ( $\text{m}^2$ ) and  $E'_{25}$  is the normalised block kinetic energy. The subscript 25 refers to the ratio of accepted downhill face displacement with respect to the structure width (here, 25%) and is implicitly associated to the value of 250.

The validity domain of the criterion presented in equation 4.1 is defined by the experimental conditions, in terms of RPEs characteristics and impact loading. In particular, it is valid for reinforced RPEs only. For unreinforced structures, it is proposed to limit  $E'_{25}$  to 0.5, based on small-scale experiments conducted by Brandl and Blovsky [2004].



**Figure 4.2** Impact response of the RPEs presented in Fig. 4.1 in terms of their downhill face displacement vs. the impacting block kinetic energy. [Lambert and Kister, 2018]

#### 4.2.1.3 Application to existing RPEs

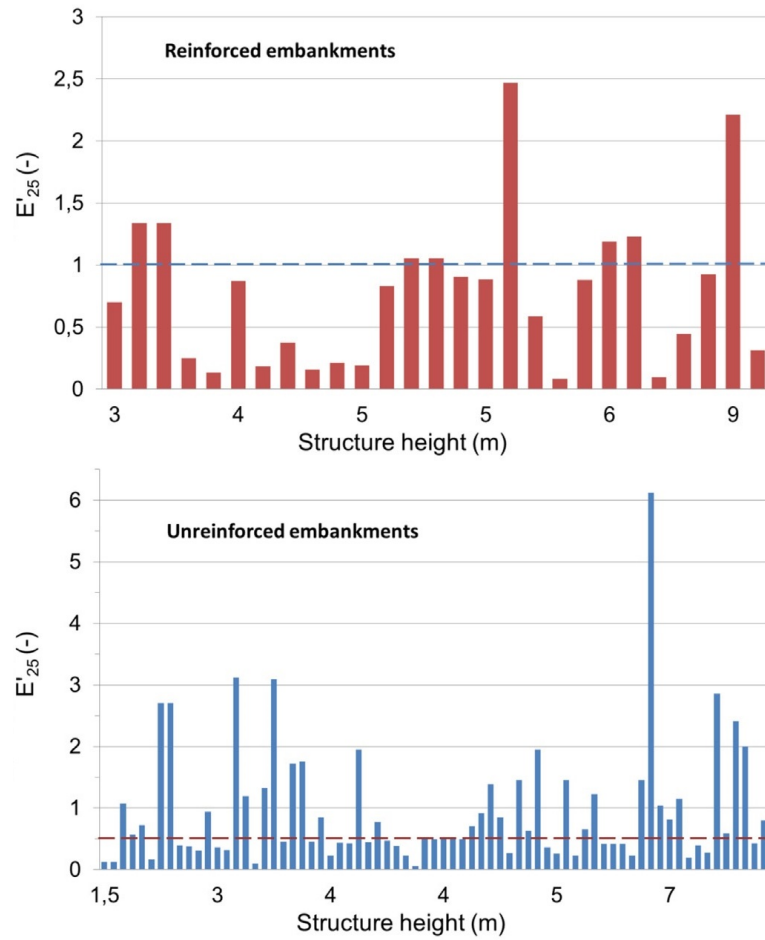
The impact strength criterion was applied to a set of ninety-eight RPEs built in Switzerland and France, with sufficiently detailed documentation. On the average these RPEs were built 10 years ago, the oldest being 30 years old. The height of these structures ranges from 1.5 to 13.2m. Their declared capacity ranges from 0.16 to 60MJ but only one sixth of these RPEs was designed accounting for the impact.

The  $E'_{25}$ -based criterion is applied differentiating reinforced and unreinforced structures (Fig. 4.3). More than 50% of the RPEs meet the requirement, with nineteen reinforced RPEs exhibiting a  $E'_{25}$  value less than 1 and thirty-five unreinforced RPEs exhibiting a  $E'_{25}$  value less than 0.5. Focusing on the cases within the criterion validity domain, it appears that thirty-two out of thirty-six RPEs meet the criterion.

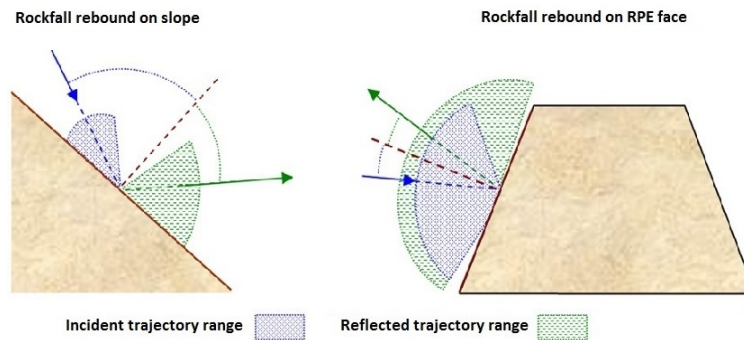
At the extreme, this figure draws the attention on two reinforced RPEs and twenty-two unreinforced RPEs for which the  $E'_{25}$  is twice the threshold. These are considered as potentially highly critical cases. Nevertheless, no definitive bad evaluation may be drawn from this expedient analysis as all these cases fall out of the criterion validity domain. Complementary analysis could be conducted to assess the impact strength of these RPEs based on more in-depth investigations and calculations. To a lesser extent, this also concerns intermediate cases where the  $E'_{25}$  value stands between one and two times the threshold value.

#### 4.2.1.4 Concluding remark

The proposed literature-based criterion was kept simple to be applied to a wide variety of RPEs, even when the available documentation is sparse, that is the general case when considering existing RPEs. It is expedient and may be used for screening large RPE collections and when revising hazard maps or risk prevention plans where existing RPEs are involved. It identifies potentially undersized RPEs, though it is not intended for design purpose.



**Figure 4.3** Assessment of existing RPEs based on the impact strength criterion (dash line) : reinforced (top) and unreinforced structures (bottom). [Lambert and Kister, 2018]



**Figure 4.4** Differences in rock block rebound conditions between a slope and the front face of a RPE. [Lambert et al., 2013]

## 4.2.2 Ability in controlling rock blocks trajectories

### 4.2.2.1 Context

Rockfall hazard assessment studies generally rely on rockfall trajectory simulation results, also providing statistical descriptors of the block passing height and kinetic energy distributions that are required for designing protective structures. In the principle, these codes may be used for quantifying the efficiency of existing and projected RPEs in satisfactorily acting on the propagation of rock blocks towards the elements at risk. Nevertheless, two limitations with 3D simulation codes raise, leading to abnormal simulated trajectories in the RPE vicinity (DiMerl project).

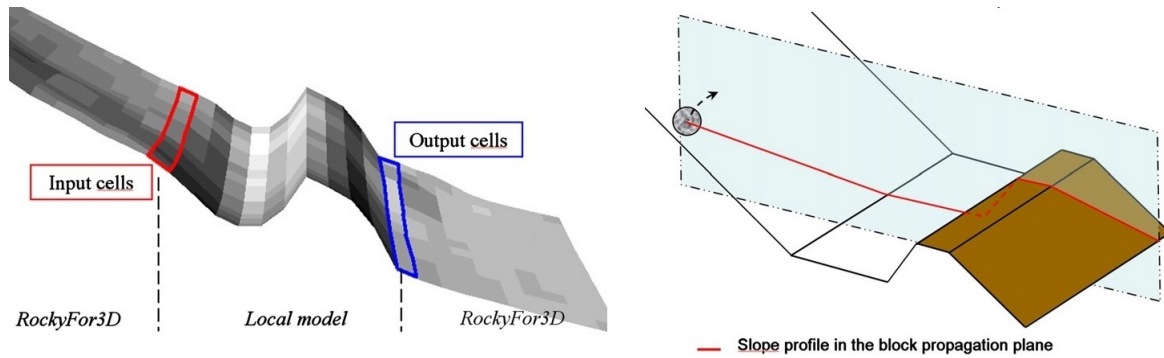
Firstly, in the daily practice of rockfall hazard assessment, the digital elevation model resolution used in 3D rasterized tool is typically 2m. This resolution, acceptable at the slope scale, is far too large for accurately describing the rapid topography changes in the RPE vicinity. As a result, the topography of both the ditch and the RPE is smoothed.

Secondly, restitution coefficients commonly used for modelling the block-soil interaction appear to be unsuitable for modelling impacts on the front face of RPEs, due to the difference in block incident trajectory orientation (Fig. 4.4). The rebound models are inappropriate for normal impacts because rebound law parameters were calibrated for shallow impacts. Also, rebound modelling approaches are over simplified, neglecting the couplings between the different components of the translational and rotational velocities.

After estimating the consequences of these limitations, the work conducted together with F. Bourrier and D. Toe consisted in proposing methods for improving the capacity of codes in modelling rockfall trajectories in the vicinity of RPEs Lambert et al. [2013].

### 4.2.2.2 Developed solution

As for the topography description issue, upgrading the resolution of the 3D elevation model in view of allowing for a precise description of the geometry of RPEs would adversely affect the



**Figure 4.5** The 3D elevation model, at the slope scale (left), is coupled to a 2D propagation model in the RPE vicinity (right). [Lambert et al., 2013]

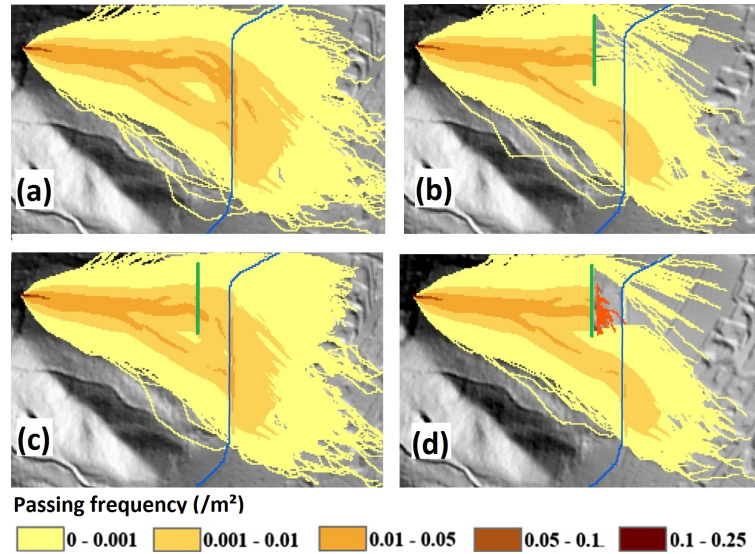
computation costs due to the dimensions of the slope to model. In lieu, the proposed solution consists in coupling a classical trajectory tool at the slope scale to a local 2D trajectory model in the RPE vicinity (Fig. 4.5). The exact RPE profile in the rockfall propagation direction is thus accounted for, by contrast with the smoothed profile at the slope scale (Fig. 4.5, left). The coupling consists in exchanging data from one model to the other at cells delineating the spatial extension of the local model (input/output cells in Fig. 4.5, left).

Limitations in the rebound model have been circumvented using the model proposed in Bourrier et al. [2008, 2009]. This stochastic model is calibrated for any incidence angle from shallow to normal impacts. The different components of the boulder rebound velocity are calculated using this stochastic rebound model from all the components of the incident velocity. The main processes governing the boulder rebound in the ditch and on the RPE face were thus accounted for, as well as their variability.

#### 4.2.2.3 Application to a real case

The proposed approach was applied to a specific case, for assessing the efficiency of the proposed approach with respect to currently used tools (Fig. 4.6). Simulations were performed using *RockyFor3D*, a stochastic rockfall trajectory simulation model considered representative of available tools. It concerned a single block released 500 000 times on a 260m long slope with a local angle ranging from 10 to 60° and terminated by the road to protect.

Simulations considering the natural slope reveals that the maximum reach probability along the road was as high as 1 % per meter of road (Fig. 4.6, a). For illustration purpose, the RPE efficiency assessment is restricted to the road section exposed to the higher hazard. The position of the upper edge of the front face of the projected RPE is represented by the green line in Figure 4.6, b. This latter figure presents results of simulations conducted on the same digital elevation model but intercepting all the blocks whose passing height along the green line is below 5.5 m. It reveals a drastic reduction of the maximum hazard along the concerned road section down to a value of 0.002 %. Still using a classical tool but integrating a 5.5m in height RPE in the digital elevation model, propagation simulations result in a much



**Figure 4.6** Simulated block trajectories: natural slope (a), intercepting all the blocks passing less than 5.5m above the natural ground (b), running classical simulations while considering the RPE in the digital elevation model (c) and using the proposed approach (d). The blue line is the road to protect. The green line shows the position of the top edge of the RPE front face.[Lambert et al., 2013]

higher number of blocks reaching the same road section (Fig. 4.6, c). A detailed investigation revealed unrealistic passing heights downwards the RPE crest line, with values exceeding 30m, resulting from the limitations mentioned earlier. The last figure shows that, running the same simulations using the proposed approach, the rock blocks are satisfactorily stopped, with a maximum hazard along the road down the RPE vanishing to  $2.10^{-4}$  % per meter of road. The higher efficiency of the RPE observed based on these simulation results as compared to the simulation results presented Figure 4.6, b is attributed to the topography changes associated with the ditch and the RPE, that are not considered in this latter case.

## 4.3 Flexible barriers

### 4.3.1 Context

By contrast with RPEs, the efficiency of barriers in reducing rockfall hazard down the slope is mainly dependent on their impact strength. Failures of existing barriers in arresting the block with dramatic consequence are primarily due to insufficient impact strength.

In the current engineering practice, the appropriate flexible barrier for a specific rockfall-prone site is notably selected based on a comparison between a unique block kinetic energy issued from trajectory simulations and the impact strength of commercially available barriers. The impact strength of flexible barriers is essentially based on the results of the impact tests



prescribed by the EAD [EOTA, 2018], whose limitations are pointed out in the introduction (sec. 1.3.3).

The previous chapter has shown that numerical models of barriers may be used a predictive manner, when well calibrated and validated against experimental data, allowing for a quantitative assessment of their mechanical response and strength to rock impact. These models make it possible to better quantify the rockfall risk reduction resulting from the use of flexible barriers. The main obstacle in view of using simulation results in an operational context is the computation time required for simulating the barrier responses to the very large possible loading cases, associated with the variability in trajectories for a same rock block.

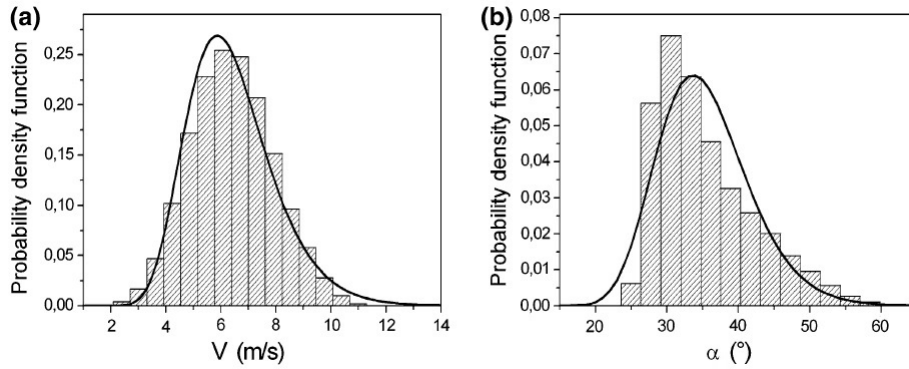
In this context, we initiated the development of computation-cost efficient methods for integrating the variability in loading conditions in the design of barriers. This work is based on simulations of the barrier impact response, using a deterministic model and considering variable loading cases. It consisted in three successive main steps. First, a probabilistic approach was used for investigating the influence of the block translational velocity and incidence angle on the response of a tree-supported barrier. Second, a meta-modelling approach was employed for generating the envelop response of a cable-net barrier while considering six parameters describing the impact conditions. The last step consisted in using this meta-model for quantifying the real efficiency of this barrier on a specific case, after coupling with a trajectory simulation tool.

This work was conducted in the context of collaborations with F. Bourrier and D. Toe (INRAe), J. Baroth (3SR), G. Gottardi, L. Govoni and A. Mentani (University of Bologna, Italy). These collaborations resulted from a committed project dynamics, centred on common concerns, with the aim of gathering researchers with different backgrounds. These collaborations thus offered us the opportunity to combine skills on different tools and methods, resulting in a significant improvement of protective structures design approaches [Bourrier et al., 2015, 2016; Mentani et al., 2016; Toe et al., 2018a].

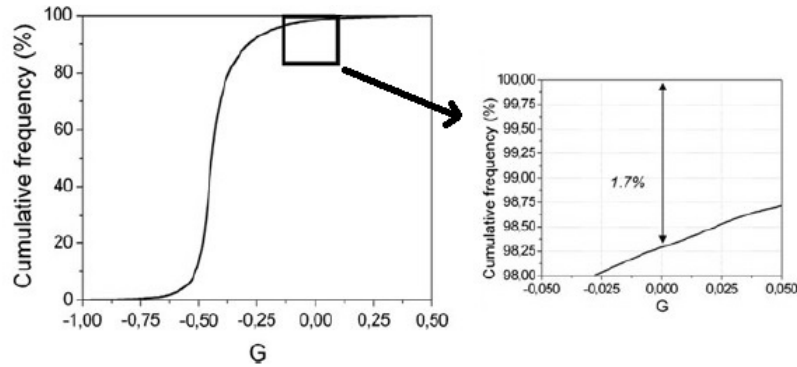
### 4.3.2 Two-parameter probabilistic design

The influence of the incident rock block kinematics on the efficiency of a flexible barrier in withstanding impacts was studied considering specific site and barrier [Bourrier et al., 2015]. For the first time a probabilistic reliability analysis was proposed combining loading cases from rockfall propagation simulations with numerical simulations of the barrier impact response. The targeted advantage of such a reliability-based approach is that statistically relevant results concerning the barrier's efficiency can be obtained based on a limited number of simulations of the barrier response.

The approach was applied to the design of a low energy tree-supported barrier for which a three-dimensional discrete element method model was developed. Probabilistic data concerning the rock block kinematics at the structure location were issued from simulations with *RockyFor3D*. For approach presentation and validation purposes, two random variables (i.e. uncertain parameters) were considered in the study: the rock block translational velocity and



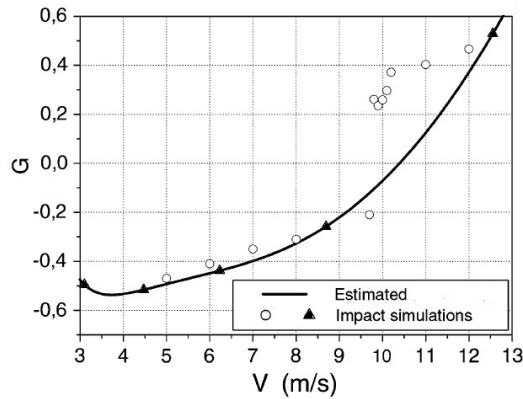
**Figure 4.7** Rock block translational velocity (a) and impact angle (b) at the barrier location. Distributions from *RockyFor3D* and their log-normal approximations. [Bourrier et al., 2015]



**Figure 4.8** Cumulative distribution of the performance function  $G$ , considering the only incident velocity as random variable. [Bourrier et al., 2015]

its angle of incidence before impact (Fig. 4.7). For these simulations, the barrier was impacted in its center and the rotation velocity was fixed to the mean value out of the trajectory simulation results. The barrier efficiency was evaluated based on a performance function,  $G$ , computed as the ratio between the translational velocity of the block after impact to that before: failure in arresting the rock block thus corresponds to the cases where  $G > 0$ .

The method consists first in running simulations of the barrier response to a few loading cases. Each case is defined as a set of specific values for each barrier design input parameter considered as random. The distribution curve of the performance function  $G$  is then reconstructed from the results of these few simulations. This reconstruction makes use of the statistical distribution associated with each random variable as deduced from rock blocks trajectory simulations conducted on the study site (Fig. 4.7). For example, Figure 4.8 shows the distribution of the performance function obtained considering the only incident translational velocity as random. According to this figure, the failure probability of this barrier on this site is less than 1.7 %.



**Figure 4.9** Barrier performance as a function of the rock block incident velocity : Comparison of simulation results (circle) to the estimation based on five simulation results (triangles). The impact leads to failure if  $G > 0$ . [Bourrier et al., 2015]

The value in this approach is demonstrated in terms of computation cost. When considering two random variables, only twenty-five simulations of the barrier response are necessary for computing a statistically relevant barrier failure probability, while classical Monte Carlo simulations would require several hundred impact simulations.

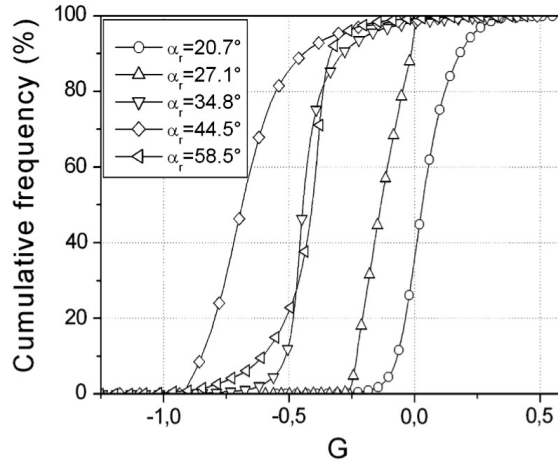
Even though the method ensures the statistical relevance of the results, a detailed comparison revealed a limitation in this approach. Above the rock block velocity leading to the structure failure ( $v > 9.5$  m/s), the prediction fails in reproducing the discontinuity observed from direct simulations (Fig. 4.9). In other words, the post impact rock block velocity is underestimated by the proposed model when  $G > 0$ . Nevertheless, this difference between the prediction and the simulation has no influence on the failure probability, as it only influences the rock block velocity in case of barrier failure.

Additionally, the study revealed the influence of the trajectory inclination on the structure response (Fig. 4.10), with a higher failure probability in case of shallow impacts. This was attributed to a much higher maximum admissible energy for inclined impacts as a result of the difference in barrier loading. This clearly shows the importance of also accounting for the trajectory inclination of the rock block in the barrier design.

All in all, the method appears rather reliable and computation-cost efficient in view of quantifying the efficiency of the barrier while considering two random variables. Nevertheless, a much larger number of input parameters are necessary for precisely describing the loading by the rock block in terms of impact point location and velocity. This motivated investigating the feasibility of using meta-models in this purpose.

### 4.3.3 Metamodel-based approach

This work was conducted considering a specific barrier type for which the University of Bologna developed and validated a FE model. This 3m in height barrier features an in-

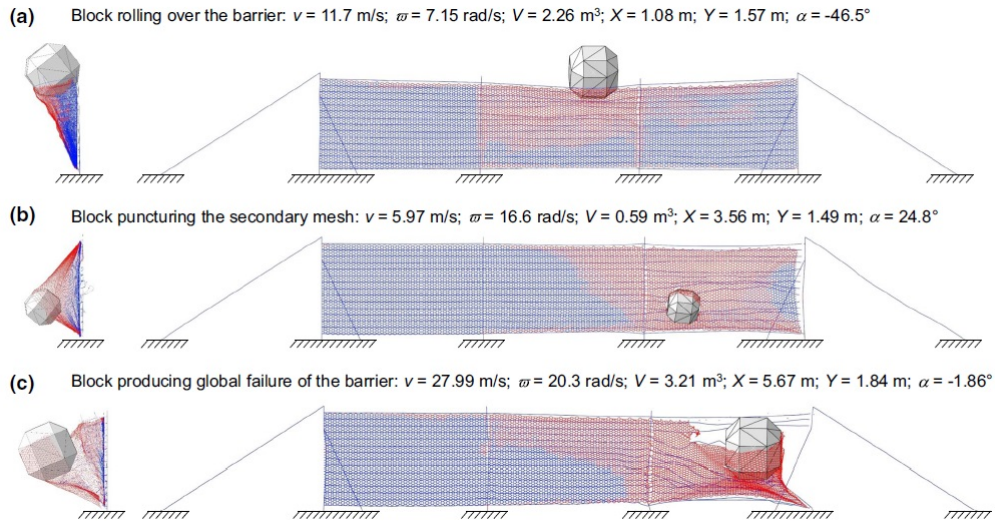


**Figure 4.10** Cumulative distribution of the performance function  $G$  under loading conditions for which the velocity is the only random variable and for different impact angles. [Bourrier et al., 2015]

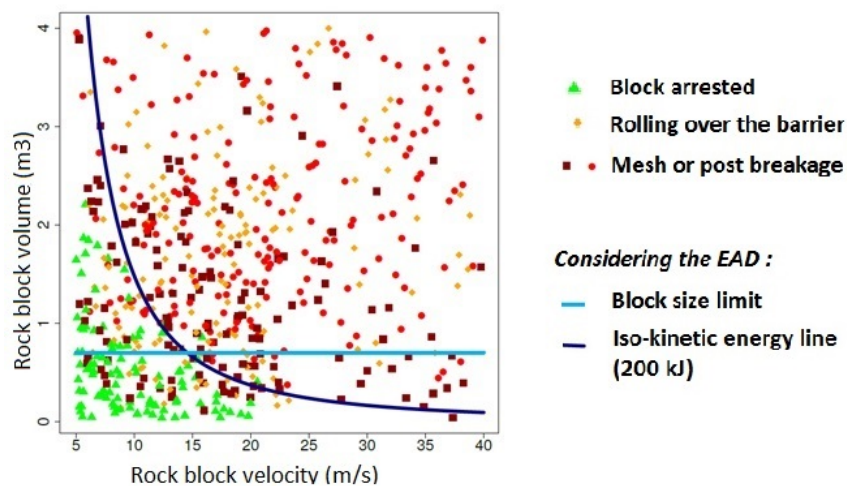
terception structure made of a hexagonal wire mesh supported by longitudinal cables passing through fix posts. Simulations confirmed that depending on the impact conditions failure in arresting the block may result from the block rolling over the barrier, perforation of the mesh or damage to posts and supporting cables (Fig. 4.11). In addition, simulations conducted in similar conditions as that prescribed by the EAD led to a reference barrier capacity of 200 kJ, above which barrier rupture is observed.

An exhaustive study of the barrier capacity in arresting the block was conducted varying 6 inputs parameters related to the block mass, impact point location, translational and rotational incident velocities over realistic variation ranges. The results are presented in Figure 4.12 with respect to the block volume and translational velocity, that are the two prevailing parameters in the barrier design. Each symbol refers to a specific loading case, with specific sets of values for the six input parameters. Green triangles stand for cases where the block was arrested while other symbols stand for cases where the barrier failed in arresting the block, following one mode or another.

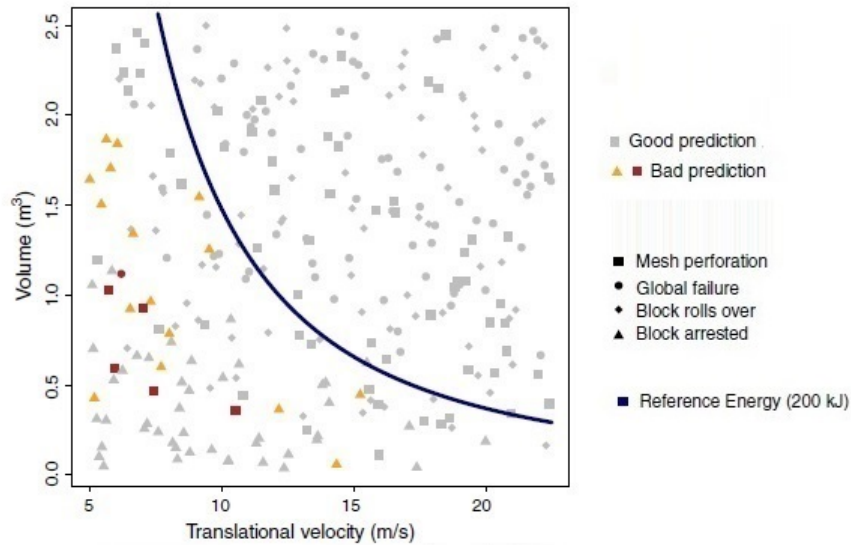
Following the EAD recommendations, the investigation is restricted to the domain where the block size is less than one-third the barrier height and where the kinetic energy is less than the reference barrier capacity, that is to say below the block size limit (volumes less than  $0.7 \text{ m}^3$ ) and the iso-kinetic energy line drawn Figure 4.12. In this domain, the barrier may be expected to be fully efficient. However, 33% of the cases in this domain lead to failure in arresting the blocks, demonstrating that the use of a unique reference capacity value, issued from a test according to the EAD, might be significantly non-conservative for assessing the on-site efficiency of this barrier. It basically emphasizes that the block volume and velocity are not sufficient for assessing the barrier response, and that the other parameters describing the impact conditions should be considered as well.



**Figure 4.11** Varying the impact conditions, different barrier failure modes may be observed: block rolling over the barrier (a), mesh perforation (b) and global failure (c). Simulations from A. Mentani (U of Bologna). [Toe et al., 2018a]



**Figure 4.12** Simulation of the barrier efficiency in arresting the block varying the impact conditions. Adapted from [Toe et al., 2018a]



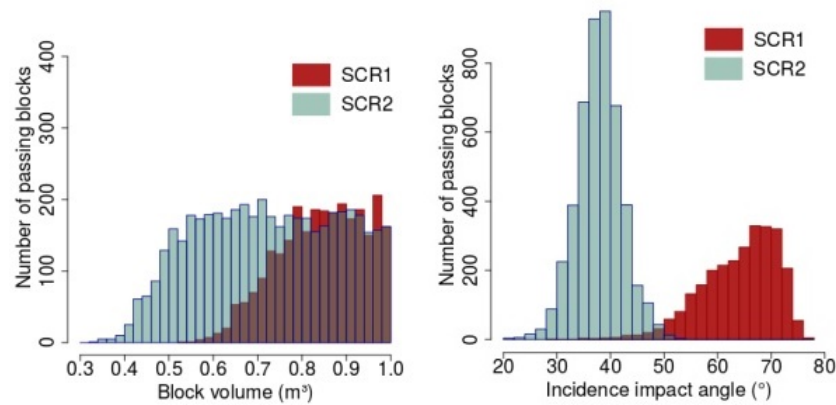
**Figure 4.13** Assessment of the meta-model predictions: Good predictions are indicated by grey symbols. The shape of the symbols indicates the mode of failure. [Toe et al., 2018a]

A meta-modelling approach was considered in the aim of developing an expedient tool for quantifying the efficiency of a barrier in arresting blocks while taking into account precisely the impact conditions. In this context, a meta-model can be defined as a mathematical operator describing the response envelop related to a specific feature of the barrier behaviour. In this context, the main feature to consider is the barrier ability in stopping the rock block, with two possibilities: success or failure. The meta-model was created based on 280 simulations of the barrier response considering different combinations of the 6 input parameters, sampled over ranges relevant to the barrier capacity. As dealing with two classes (failure/success), the meta-model was created using a support vector machine (SVM). The SVM allowed defining the optimal 6-D hyperplane, in a space of the input parameters, separating the region associated with success to that associated with failure of the barrier in arresting the rock blocks.

The relevance of the meta-modelling approach in predicting success or failure, estimated comparing the meta-model estimations with FE simulation results and using the leave-one-out cross-validation method, was found to exceed 90 %. More precisely, it failed in predicting 3% of the failure cases (Fig. 4.13). Restricting the analysis to the cases falling within the domain defined in Figure 4.12, this value reaches 4.5% which is very low compared to 33% when considering the barrier reference capacity.

All in all, the meta-model is shown to be effective in predicting the barrier ability in arresting blocks to any impact conditions. An accurate meta-model is reached at the cost of 280 simulations of the barrier impact response, providing a formidable tool to help in the design of these structures.

Furthermore, allowing to accommodate the effects of the impact conditions on the prediction of the barrier response, the approach can be successfully used in combination with



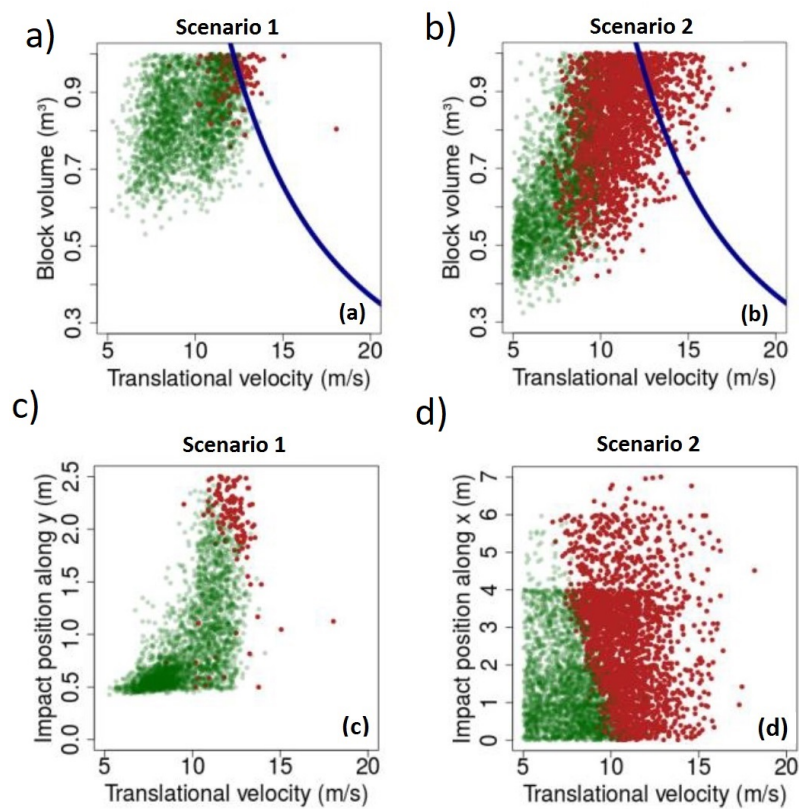
**Figure 4.14** The 2 scenarios in particular differ by the distribution of the mass and trajectory inclination angle of the blocks reaching the barrier. [Lambert et al., 2021]

rockfall trajectory simulation tools to improve rockfall quantitative hazard assessment and optimise rockfall mitigation strategies.

#### 4.3.4 Application to real cases

Due to its mathematical structure and computational cost-effectiveness, the meta-model can be easily coupled with a probabilistic rockfall trajectory simulation tool to statistically quantify success or failure of the barrier in arresting the blocks. The meta-model was coupled to *RockyFor3D* for applying the method to two real situations exhibiting similar slope characteristics and considering the same uniform volume distribution for the released blocks. The number of blocks reaching the barrier locations was 2,677 and 4,712 for the first and second scenarios respectively. In both cases the block size, kinetic energy and passing height at the barrier locations were in accordance with the barrier characteristics [Toe et al., 2018b]. Indeed, 95 % of the blocks had a kinetic energy less than the barrier reference capacity (200 kJ) and a passing height less than 2.5m. Nevertheless, the distribution of all the parameters describing the impact conditions were different between the two scenarios. This in particular concerned the block passing height and kinetic energy as well as the volume of the block and its incidence angle (Fig. 4.14). The difference in volume of block reaching the barrier is explained by the fact that in the first scenario smaller blocks stop before reaching the barrier.

As a result of these differences in impact conditions, a huge difference in barrier efficiency in arresting the blocks is observed from one scenario to the other. The meta-model predicts a 5% failure probability for the first scenario compared to 47% for the second one (Fig. 4.15, a and b). Restricting the analysis to cases below the 200-kJ limit results in respective failure probabilities of 3 and 42%. This difference appears really high considering the fact that the two scenarios had similar statistical descriptors for the block kinetic energy and passing height. This differences in barrier efficiency results from the difference in distribution of all the other parameters describing the impact conditions.



**Figure 4.15** Meta-model estimation of the success (green) and failure (red) of the barrier in arresting the blocks. For both scenarios, the failure/success occurrence for a given block depends on the translational velocity (a, b). It also depends on the impact height for the first scenario (c) and on the horizontal distance to the barrier center for the second one (d). [Lambert et al., 2021]



A detailed investigation of the results confirmed the well established trend that the parameter with the highest influence on the structure response was the block translational velocity. In addition, the barrier failure is related to other parameters whose influence was found to differ from one scenario to the other. In the first scenario, failure is associated to impacts by blocks with high passing heights (Fig. 4.15, c) whereas it is associated with impacts at distance from the barrier center along the horizontal axis in the second scenario (Fig. 4.15, d). These differences clearly result from the observed differences in variation range and distribution of parameters others than the block kinetic energy.

From an operational perspective, these results clearly demonstrate that defining a rockfall protection barrier based on statistical descriptors of the block kinetic energy distribution and of the block passing height distribution is not sufficient for guaranteeing its ability in reducing the hazard down to the targeted value. More precisely, a barrier design based on the EAD approach may not prevent from a high barrier failure probability on real sites, with values as high as 40%, as in the illustration case.

#### 4.3.5 Concluding remark

The literature proposes more and more FEM and DEM numerical models for simulating the response of barriers to rockfall impacts, for various barrier technologies. Some of these models have been shown to be relatively computationally inexpensive, with computation times of a few minutes for simulating one impact. This efficiency is nevertheless insufficient for providing statistically relevant data related to the on-site barrier efficiency. Meta-models allow circumventing this limitation, making it a powerful and reliable approach in view of improving the quantification of the hazard reduction resulting from the building of a barrier.

Meta-model creation tools are now widely available through user-friendly softwares. Creating a meta-model is affordable in terms of computation time. This requires very limited time and effort, in particular by contrast with that required for developing and validating a numerical model for a specific barrier.

Meta-models will lead to a significant improvement of quantitative rockfall hazard assessment when in the presence of protective barriers. It will allow a much more reliable barrier efficiency assessment than considering the maximum energy level obtained based on the EAD prescriptions.

## 4.4 Synthesis

This chapter has focused on the evaluation of the efficiency of protection structures. Three main issues were considered. First, an expedient impact strength criterion was developed for rockfall embankments. Second, an improved approach was proposed for conducting trajectory simulations in the presence of embankments, in view of a better design with respect to block trajectory control. Last, the benefit in using meta-models in view of better quantifying the efficiency of barriers in arresting rock blocks was demonstrated.

The presented achievements are mostly based on the works presented in the previous chapters and result from the merging of various knowledge and skills, possessed by different people I collaborated with.

All these achievements constitute tools that can be used in operational contexts, in particular for improving the design of structures as well as for designing and assessing the efficiency of protection structures for a given site.

## Chapter 5

# Ongoing projects

The efficiency assessment and improvement of structures acting as passive protection against gravity driven natural hazards confronts practitioners with challenges, raising many issues to be addressed by the research community. These questions globally relate to the response of structures to various and complex interactions with rockfall, debris flows and snow avalanches. As illustrated in the previous chapters, addressing these issues requires to mobilize various tools, methods and skills.

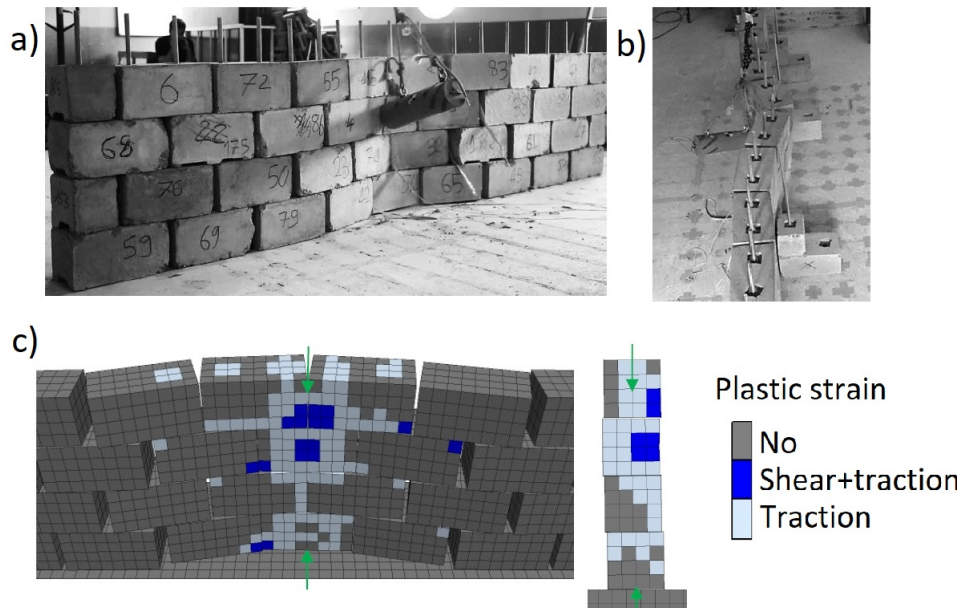
This chapter gives a glimpse into two ongoing projects. As these works are not completed and their results not published, this presentation is kept brief. These ongoing projects constitute a combination of works in the continuation of previous ones and openings on new research topics.

### 5.1 Articulated rockfall protection wall

In view of proposing slender rockfall protection structures, the Bloc Armé technique is being developed by two companies, namely Géolithe and Géolithe Innov. This technique relies on the use of interconnected concrete blocks to form articulated walls. The development of this technique is based on experimental investigations and numerical simulations. This work was part of the PhD thesis of A. Furet (Cifre thesis, funded by Géolithe), cosupervised by P. Villard (3SR) and I.

The impact response of this type of rockfall protection structure is investigated at the real scale and at the reduced scale. Based on these experiments, a numerical model of the wall is developed using a finite difference software (FLAC3D), with the aim of simulating the global structure response, in terms of displacement in particular. This model is intended to be used in operational contexts, for design purpose. Thus, the concrete block modelling is intentionally kept simple (shape, constitutive laws, space discretisation).

The experiments at the reduced scale allows investigating the qualitative influence of some parameters related to the impact conditions (height and energy) and to the structure design (simple wall or wall reinforced with shear walls)(Fig. 5.1). The structure design



**Figure 5.1** Impact experiments on a reduced-scale Bloc Armé wall, 0.8 m in height and reinforced with shear walls. Experiments (a, b) and numerical simulation results (c). [Furet et al., 2020]

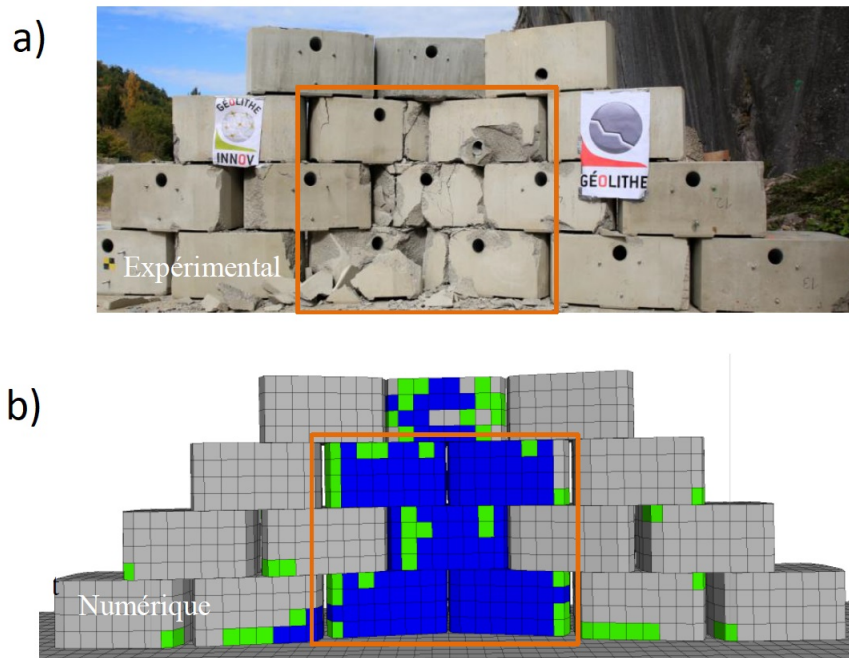
appears to have a strong influence on the mechanisms governing the structure deformation and energy dissipation. The developed model reveals appropriate for mimicking the structure displacement, in the various investigated configurations.

The investigation at the real scale confirms the ability of the model in satisfactorily simulating the structure impact response (Fig. 5.2). Globally, the structure deformation is well predicted. More locally, the plastic strain observed in the simulation exhibits similar features as during the experiments.

The next step will consist in improving the model so that high kinetic energy impacts on Bloc Armé structures with complex geometries can be modelled. Simulation results will be compared to results from real-scale impact experiments to be conducted soon, in the framework of the C2ROP project. This improvement will in particular require addressing the key question of the correct modelling of the various energy dissipating mechanisms. This step-by-step work should result in a model with good predictive capacities allowing developing the technique by considering various designs, in terms of geometry in particular.

## 5.2 Barriers in torrential context

Barriers are more and more widely used in torrents for containing flow-entrained solid materials such coarse granular materials contained in debris flows or floating wood. The containment

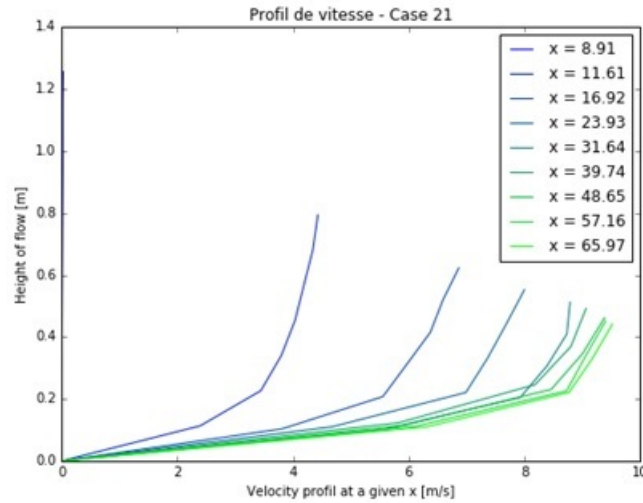


**Figure 5.2** Impact on a real-scale Bloc Armé wall (3.2 in height). After successive impacts (a) and simulation results (b).

of debris flow is at the heart of the Pridyn project while floating wood is being addressed in the framework of the Filtor project.

The numerical component of the Pridyn project allowed developing a model accounting for the peculiarities of the barrier technology owned by the project leader (NGE Fondations) [Dugelas et al., 2019; Dugelas, 2020]. As for the use of these barriers in torrents, the project aims at proposing an optimised barrier design based on experiments in the field and numerical simulations. The experiments concern a real barrier equipped with various sensors for obtaining data related to the barrier response when exposed to a real event. Real time measurements concern loads transmitted in the barrier main cables and deflection of the barrier, as well as the main characteristics of the incoming flow (velocity, height). The system is developed together with H. Bellot and F. Fontaine (INRAe). It also integrates a data acquisition triggering system, video recorders and a remote control system. This equipment will be installed soon on a real barrier.

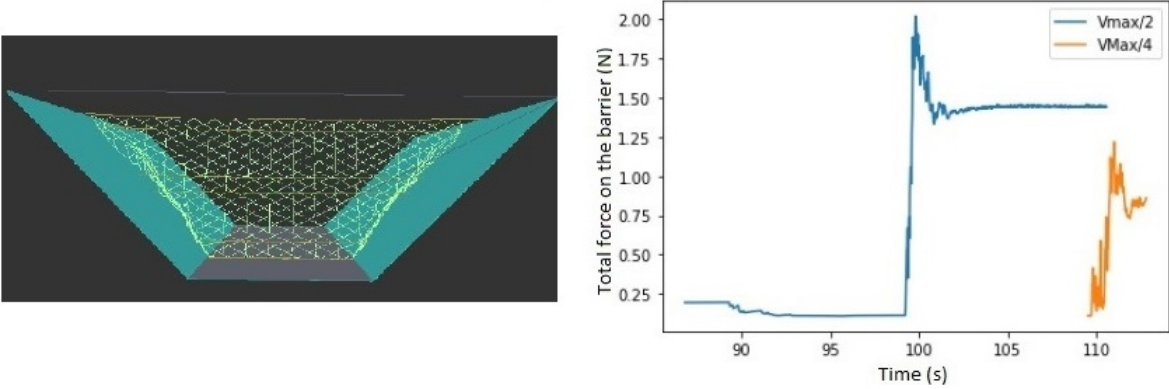
The barrier numerical model is adapted from Dugelas [2020] in order to account for the specific design of such barriers when used in torrents. These adaptations concern the barrier dimensions, the barrier components and their lay out in the barrier. In parallel and more noticeable, a new model of the flowing material is developed. By contrast with the model proposed by Albaba et al. [2015], this new model accounts for the presence of the liquid matrix in between the boulders, stones and pebbles transported by the debris flow. In this purpose, we used the interaction law recently implemented in the Yade software that is based



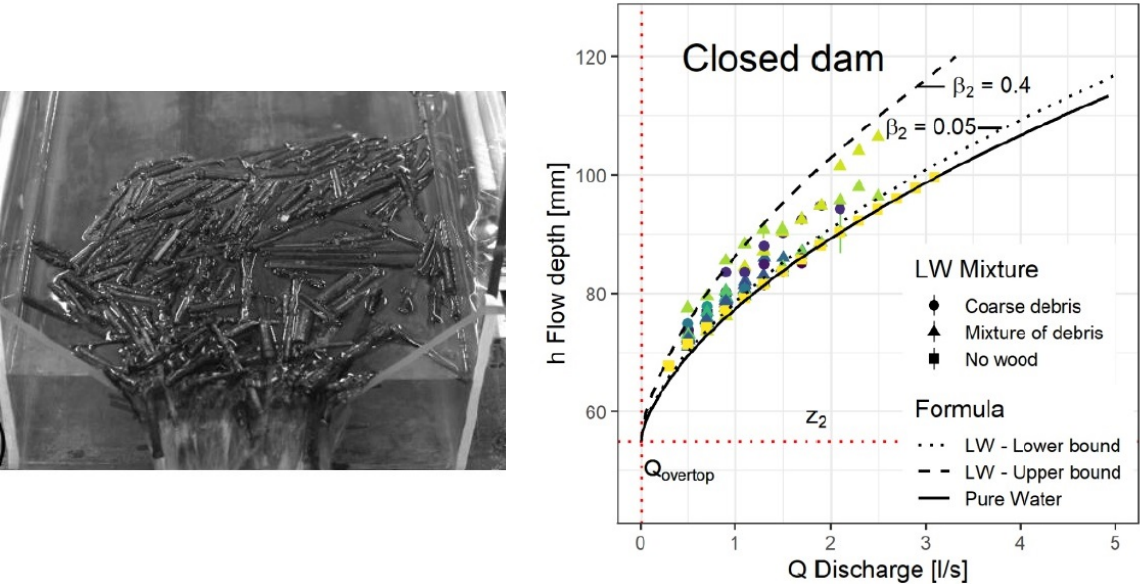
**Figure 5.3** The debris flow model reveals efficient in generating flows with realistic velocity profiles along the flume.

on Chèvremont et al. [2019]. This law accounts for viscous damping associated with variations in inter-particle distance. It was calibrated for this specific context of use. In addition to this law, a specific algorithm is proposed for simulating the inertial effects on each solid particle associated with the debris flow displacement. This consists in applying on each particle a force proportional to the difference in velocity between the particle and the particles mean velocity. This modelling strategy reveals efficient in simulating the propagation of debris flows down a flume, in terms of propagation velocity and velocity profile (Fig. 5.3). This model is used for running simulations varying parameters related to the flow characteristics and considering a real barrier in realistic conditions (Fig. 5.4). Further developments are necessary in particular for guaranteeing the model robustness. In a more distant future, the simulation results will be compared to data measured on the real site, for model optimisation and validation purpose. It will then be possible to study the response of any barrier to any debris flow, in particular in view of improving the design of such structures.

More recently, the Filtor project was initiated in view of addressing the efficiency of barriers in satisfactorily intercepting floating woods. Based on small scale experiments in the lab, the main aim is to investigate the retention capacity of these barriers. One question relates to the occurrence of massive floating wood sudden release resulting from barrier over topping. For these experiments, particular attention is paid to similitude issues with respect to the barrier mechanical characteristics. Experiments on these barriers are underway. As a first stage, the question of floating wood retention capacity of more classical civil engineering structures is addressed, focusing on head losses and release conditions associated with different types of open check dams (Fig. 5.5).



**Figure 5.4** Influence of the debris flow volume on the total force applied on a barrier in real configuration.



**Figure 5.5** Interception of floating wood by a rigid structure. Top view during small scale experiments and influence in terms of flow depth vs discharge. [Piton et al., 2020].





# Bibliography

- Albaba, A., Lambert, S., and Faug, T. (2018). Dry granular avalanche impact force on a rigid wall: Analytic shock solution versus discrete element simulations. *Phys. Rev. E*, 97:052903.
- Albaba, A., Lambert, S., Kneib, F., Chareyre, B., and Nicot, F. (2017). Dem modeling of a flexible barrier impacted by a dry granular flow. *Rock Mechanics and Rock Engineering*, 50(11):3029–3048.
- Albaba, A., Lambert, S., Nicot, F., and Chareyre, B. (2015). Relation between microstructure and loading applied by a granular flow to a rigid wall using dem modeling. *Granular Matter*, 17(5):603–616.
- Bertrand, D. (2006). *Modélisation du comportement mécanique d'une structure cellulaire soumise à une sollicitation dynamique localisée - Application aux structures de protection contre les éboulements rocheux*. PhD thesis, Université Joseph Fourier, Grenoble.
- Bertrand, D., Gotteland, P., and Nicot, F. (2005). Dem modelling of natural stones assembly confined in wire mesh. In *Powders and Grains*, Stuttgart (Germany).
- Bertrand, D., Nicot, F., Gotteland, P., and Lambert, S. (2006). Modelling a geo-composite cell using discrete analysis. *Computers and geotechnics*, 32:564–577.
- Bourrier, F., Baroth, J., and Lambert, S. (2016). Accounting for the variability of rock detachment conditions in designing rockfall protection structures. *Natural Hazards*, 81(1):365–385.
- Bourrier, F., Dorren, L., Nicot, F., Berger, F., and Darve, F. (2009). Toward objective rockfall trajectory simulation using a stochastic impact model. *Geomorphology*, 110:68–79.
- Bourrier, F., Lambert, S., and Baroth, J. (2015). A reliability-based approach for the design of rockfall protection fences. *Rock Mechanics and Rock Engineering*, 48(1):247–259.
- Bourrier, F., Lambert, S., Heymann, A., Gotteland, P., and Nicot, F. (2011). How multi-scale approaches can benefit cellular structure design. *Canadian geotechnical Journal*, 48:1803–1816.
- Bourrier, F., Nicot, F., and Darve, F. (2008). Physical processes within a 2d granular layer during an impact. *Granular matter*, 10(6):415–437.

## BIBLIOGRAPHY

---

- Brandl, H. and Blovsky, S. (2004). Protective barriers against rockfall. In *3rd European geosynthetics conference (Euogeo 3)*, pages 95–100, Munich, Allemagne.
- Breugnot, A., Lambert, S., Villard, P., and Gotteland, P. (2016). A discrete/continuous coupled approach for modeling impacts on cellular geostructures. *Rock Mechanics and Rock Engineering*, 49(5):1831–1848.
- Calvino, A., Dumont, P., Durville, J.-L., Dussauge, C., Effendiantz, L., and Evrard, H. (2001). *Parades contre les instabilités rocheuses*. Collection environnement. LCPC, Paris.
- Castanon-Jano, I., Blanco-Fernandez, E., Castro-Fresno, D., and Ballester-Munoz, F. (2017). Energy dissipating devices in falling rock protection barriers. *Rock Mechanics and Rock Engineering*.
- Chèvremont, W., Chareyre, B., and Bodiguel, H. (2019). Quantitative study of the rheology of frictional suspensions: Influence of friction coefficient in a large range of viscous numbers. *Phys. Rev. Fluids*, 4:064302.
- Coulibaly, J., Chanut, M.-A., Lambert, S., and Nicot, F. (2017). Nonlinear discrete mechanical model of steel rings. *Journal of Engineering Mechanics*, 143:9.
- Coulibaly, J., Chanut, M.-A., Lambert, S., and Nicot, F. (2018). Sliding cable modeling: An attempt at a unified formulation. *International Journal of Solids and Structures*, 130-131:1 – 10.
- Coulibaly, J., Chanut, M.-A., Lambert, S., and Nicot, F. (2019). Toward a generic computational approach for flexible rockfall barrier modeling. *Rock Mechanics and Rock Engineering*.
- Dugelas, L. (2020). *Stratégies probabilistes appliquées à la modélisation numérique discrète : le cas des filets pare-pierres*. PhD thesis, Univ. Grenoble Alpes.
- Dugelas, L., Coulibaly, J., Bourrier, F., Lambert, S., Chanut, M., Olmedo, I., and Nicot, F. (2019). Assessment of the predictive capabilities of discrete element models for flexible rockfall barriers. *International Journal of Impact Engineering*.
- EOTA (2018). Falling rock protection kits. ead 340059-00-0106, 2018/c 417/07. Technical report, European Organization for Technical Approvals.
- Furet, A., Lambert, S., Villard, P., Jarrin, J., and Lorentz, J. (2020). Réponse sous impact de murs pare-blocs. *Rev. Fr. Geotech*, 9(163).
- Hennebert, P., Lambert, S., Fouillen, F., and Charrasse, B. (2014). Assessing the environmental impact of shredded tires as embankment fill material. *Canadian Geotechnical Journal*, 51:469–478.
- Heymann, A. (2012). *Approche expérimentale du comportement mécanique des géo-ouvrages à technologie cellulaire. Application aux ouvrages pare-blocs*. PhD thesis, Université de Grenoble.

- Heymann, A., Gotteland, P., and Lambert, S. (2010a). Impact load transmission within a half scale sandwich rockfall protection wall. In *Third Euro Mediterranean Symposium on Advances in Geomaterials and Structures, AGS2010*, volume 2, pages 331–36, Djerba, Tunisia.
- Heymann, A., Lambert, S., Haza-Rozier, E., Vincelas, G., and Gotteland, P. (2010b). An experimental comparison of half scale rockfall protection sandwich structures. In *11th International Conference on Structures Under Shock and Impact*, pages 15–26, Tallinn, Estonia,.
- Jiang, Y. and Towhata, I. (2013). Experimental study of dry granular flow and impact behavior against a rigid retaining wall. *Rock Mech. Rock Eng.*, page 713?729.
- Lambert, S. (2007). *Comportement mécanique de géocellules - application aux constituants de merlons pare-blocs cellulaires*. PhD thesis, Joseph Fourier, Grenoble.
- Lambert, S. (2012). Analyse technique du parc de merlons rtm. Technical report, DGPR-MEDDTL.
- Lambert, S. and Bourrier, F. (2013). Design of rockfall protection embankments: A review. *Engineering geology*, 154:77–88.
- Lambert, S., Bourrier, F., Gotteland, P., and Nicot, F. (2019). An experimental investigation of the response of slender protective structures to rockfall impacts. *Canadian Geotechnical Journal*.
- Lambert, S., Bourrier, F., and Toe, D. (2013). Improving three-dimensional rockfall trajectory simulation codes for assessing the efficiency of protective embankments. *International Journal of Rock Mechanics and Mining Sciences*, 60:26 – 36.
- Lambert, S., Gotteland, P., and Nicot, F. (2009). Experimental study of the impact response of geocells as components of rockfall protection embankments. *Natural hazards and earth system sciences*, 9:459–467.
- Lambert, S., Heymann, A., Gotteland, P., and 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. (2017a). Analysis of existing rockfall embankments of switzerland (aeres); part a: State of knowledge. Technical report, Federal Office for the Environment, Bern (CH).
- Lambert, S. and Kister, B. (2017b). Analysis of existing rockfall embankments of switzerland (aeres); part b: Analysis of the collected data and comparison with up-to-date knowledge. Technical report, Federal Office for the Environment, Bern (CH).
- Lambert, S. and Kister, B. (2018). Efficiency assessment of existing rockfall protection embankments based on an impact strength criterion. *Engineering Geology*, 243:1 – 9.

## BIBLIOGRAPHY

---

- Lambert, S., Toe, D., Mentani, A., and Bourrier, F. (2021). A meta-model-based procedure for quantifying the on-site efficiency of rockfall barriers. *Rock Mechanics and Rock Engineering*.
- Mentani, A., Govoni, L., Gottardi, G., Lambert, S., Bourrier, F., and Toe, D. (2016). A new approach to evaluate the effectiveness of rockfall barriers. *Procedia Engineering*, 158:398 – 403. VI Italian Conference of Researchers in Geotechnical Engineering, CNRIG2016 - Geotechnical Engineering in Multidisciplinary Research: from Microscale to Regional Scale, 22-23 September 2016, Bologna (Italy).
- Mölk, M. and Hofmann, R. (2011). The austrian standard onr 24810: design of rock-fall protection measures. partial factor of safety-approach and best practice for the design of rock-fall embankments. In *Proceedings of Rocexs 2011*, pages 45–46., Innsbruck, Austria.
- Piton, G., Horiguchi, T., Marchal, L., and Lambert, S. (2020). Open check dams and large wood: head losses and release conditions. *Natural Hazards and Earth System Sciences Discussions*, 2020:1–29.
- Ronco, C., Oggeri, C., and Peila, D. (2009). Design of reinforced ground embankments used for rockfall protection. *Natural hazards and earth system science*, 9(4):1189–1199.
- Simons, M., Pollak, S., and Peirone, B. (2009). High energy rock fall embankment constructed using a freestanding woven wire mesh reinforced soil structure. In *60th Highway Geology Symposium*, pages 290–301, Buffalo, New York,.
- Smilauer, V., Catalano, E., Chareyre, B., Dorofeenko, S., Duriez, J., Gladky, A., Kozicki, J., Modenese, C., Scholtes, L., Sibille, L., Stransky, J., and Thoeni, K. (2014). *Yade Documentation*. The Yade Project. <http://yade-dem.org/doc/>.
- Toe, D., Mentani, A., Govoni, L., Bourrier, F. and Gottardi, G., and Lambert, S. (2018a). Introducing meta-models for a more efficient hazard mitigation strategy with rockfall protection barriers. *Rock Mechanics and Rock Engineering*, 51(4):1097–1109.
- Toe, T., Mentani, A., Lambert, S., Govoni, L., Gottardi, G., and Bourrier, F. (2018b). A novel approach to assess the ability of a protection barrier to mitigate rockfall hazard. In *Interpraevent*, Toyama, Japan.
- Volkwein, A. (2014). Flexible debris flow barriers ? design and application. Technical report, WSL.
- Zhang, L., Lambert, S., and Nicot, F. (2017a). Discrete dynamic modelling of the mechanical behaviour of a granular soil. *International Journal of Impact Engineering*, 103:76 – 89.
- Zhang, L., Nguyen, N., Lambert, S., Nicot, F., Prunier, F., and Djeran-Maigre, I. (2017b). The role of force chains in granular materials: from statics to dynamics. *European Journal of Environmental and Civil Engineering*, 21(7-8):874–895.