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Research Paper

Efficient discrete modelling of composite structures for rockfall protection

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ABSTRACT

This paper presents a discrete framework for the modelling of composite structures for rockfall protection. The model is applied to analyse the dynamic response of a cylindrical damping module upon impact of a boulder. The damping module consists of a cylindrical wire mesh, two steel rings, a boundary rope, a geotextile lining and a granular filling material. The chain-link wire mesh, the steel rings and the boundary rope are represented with deformable cylinder elements. The geotextile lining is incorporated into the openings of the wire mesh by using deformable facets. The filling material is represented using spherical particles.

1. Introduction

Rockfalls represent a serious hazard in mountain areas and mining environments, where they can cause significant damage to infrastructures, residential buildings, working machineries and lead to numerous injuries and sometimes even fatalities. A variety of protective and mitigation measures have been designed over the last decades to dissipate and/or absorb the energy associated with rockfall impacts. The experimental and numerical research on rockfall protection structures focuses on the investigation of their efficiency with the objective to improve the current designs or propose new solutions [1]. Numerical modelling has become a valuable tool to assist practitioners and researchers with these processes.

The finite element method (FEM) and the discrete element method (DEM) are two of the most widely used numerical methods to investigate the behaviour of protective structures upon rockfall impact. The FEM is mainly used to simulate rockfall structures involving wire meshes (e.g., [2–4]). The DEM is more suitable for the modelling of high-speed dynamic impact problems involving granular materials and complex contact configurations. In particular, the DEM has successfully been applied to the numerical investigation of the behaviour of granular cushion layers undergoing rockfall impact (e.g., [5,6]), the mechanical behaviour of composite structures such as sandwich structures (e.g., [7]) and cellular structures (e.g., [8]), and for the design optimisation of rockfall embankments (e.g., [9]).

Various approaches for the modelling of composite structures for rockfall protection have been developed using the DEM. Bertrand et al. [10] modelled geo-composite cells filled with angular limestone blocks as part of cellular structures. The geo-composite cellular structure comprised of a steel wire mesh envelop. The mesh was represented by remotely interacting particles positioned at the physical nodes of the mesh. The wire model was later extended by Thoeni et al. [11] by including a stochastically distributed contact model to investigate the behaviour of rockfall draperies. The modelling of soil bags was also investigated using DEM where the geotextile was modelled using the same remote interaction concept [12]. Breugnot et al. [8] developed a model of a cellular rockfall protection embankment using a coupled discrete–continuum approach. Similarly to Bertrand et al. [10], the authors modelled geocomposite cells filled with granular material. However, the wire mesh was not directly modelled. Instead, its effects were taken into account by adding tensile forces between adjacent fill material particles situated at the periphery of the geocomposite cell. Lorentz [7] investigated the dissipation capacity of sandwich structures undergoing block impact. The investigated

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sandwich structure was a multi-layer structure composed of a concrete slab covered with a layer of tires filled with geotextile socks containing gravel. In the numerical model, the slab and the tires were represented using bonded particles. The geotextile socks were not modelled explicitly but the tires filled with gravel were enclosed by walls.

An alternative composite structure for rockfall mitigation is the damping module. It consists of a cylinder module made of a wire mesh, steel rings, an optional boundary rope/cable and a geotextile lining filled with granular materials such as sand, gravel or cellular glass. The mechanical behaviour of these systems and their application as cushion layers for rockfall galleries was experimentally investigated by Schellenberg et al. [13]. Nevertheless, the efficiency of the damping modules has never been investigated numerically and current design guidelines are based on limited experimental testing and empirical models. Recently, the mining industry considered using damping modules as energy dissipation system on the top of portal entries located at the base of highwalls. They could be an effective alternative to piles of waste rock materials commonly used for this purpose. However, a numerical tool to assist with the design and analysis of various configurations is still needed.

This paper presents a novel approach for the modelling of composite structures for rockfall protection such as damping modules. The main innovation resides in the accurate modelling and combination of all components such as wire meshes, wire ropes, geotextiles and granular material. For this purpose, the authors developed a numerical framework that includes the representations of all components and the constitutive models to handle the interactions between these elements. The numerical framework is based on the DEM and is very general. As such it can be applied to model various composite structures. In the context of this work it is applied to damping modules with the aim to provide a design tool for such structures. First, the characteristics of the damping module are presented. A detailed description of the numerical framework follows, addressing each component, the constitutive laws and the handling of the necessary contacts. Finally, the dynamic response of the damping module is validated using experimental results and the capabilities of the model is demonstrated by investigating various configurations.

2. Characteristics of a damping module

Damping modules are mainly used as cushion layer on top of rockfall galleries where they are placed on the reinforced concrete slab. In practice, the installation of damping modules requires the following steps. First, the cylinder modules are positioned on top of the reinforced concrete slab. Then, a geotextile lining is placed inside every cylinder module. Finally, the cylinder modules are filled with granular material such as sand, gravel or cellular glass.

Table 1
Characteristics of the boundary rope [15].

Type	6 × 7 FC
Material	Steel grade 1770
Young's modulus	96 GPa
Minimal breaking force	37.6 kN
Nominal diameter	$d = 8$ mm
Compactness factor	$F = 0.38$
Cross sectional area	$A_w = 24.32\ \text{mm}^2$
Approximate mass	22.1 kg/100 m

This procedure is applied to install different configurations of cushions layers using damping modules. Fig. 1(a) shows a single module and Fig. 1(b) illustrates how single modules can be combined to form a more complex structure. In the latter case, a boundary rope is used to link the modules and it is used to make the modules act like one. The boundary rope could also be used to reinforce a single module. The characteristics of the commonly used wire rope are summarised in Table 1.

This work focuses on the single module shown in Fig. 1(a). This damping module consists of a TECCO cylinder module (also referred as cylinder mesh) and a geotextile lining. The cylinder module is filled with gravel (Fig. 2). The geotextile lining keeps the granular material inside the cylinder mesh and has no major structural function. Hence, the mechanical behaviour of the damping module mainly depends on the granular material and the cylinder mesh characteristics.

The cylinder mesh is composed of a cylindrical chain-link wire mesh which is enclosed by two steel rings (Fig. 2). Those rings have a diameter of 10 mm, and their properties are listed in Table 2. The chain-link wire mesh (Fig. 3) is a Geobrugg high tensile TECCO G-65/3 of the type 83 × 143 with a wire diameter of 3.0 mm. The properties are summarised in Table 3. The mesh is assembled using single wires following a rhomboidal pattern. The single wires are bent to form the chain to chain interaction. This construction method generates an out of plane eccentricity for the chain link. The latter induces a non-linear deformation behaviour of the chain link mesh [3].

3. Numerical framework

3.1. Overview

The DEM allows the efficient modelling of the dynamic phenomena involving complex contact configurations and large displacements. Thereby bodies are generally represented by rigid locally deformable particles, mostly spheres, which interact by means of contact forces and contact moments. The interactions between each particle are considered explicitly and are generally

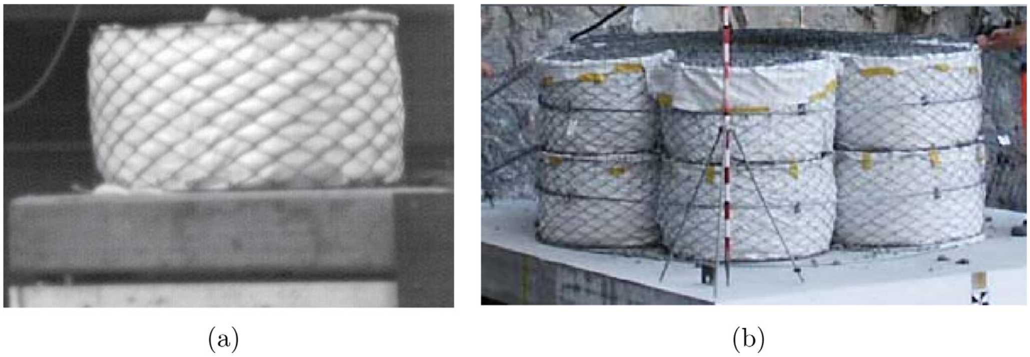
(a) (b)

Fig. 1. Damping module configurations: (a) single module and (b) combined modules with boundary rope (after [14]).