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A 3D discrete element modelling approach for rockfall analysis with drapery systems

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ABSTRACT

This paper presents a novel approach for the simulation of rockfalls behind drapery systems which can be used to accurately assess the residual rockfall hazard involved with such systems. A discrete element model of drapery systems installed on rock slopes is presented where all the relevant interactions are taken into account. The approach is based on the classical discrete element method, where the block is represented by a rigid assembly of spheres. The slope is represented by triangular elements and the drapery is represented by spherical particles which interact remotely. The model is calibrated and validated by comparing the numerical predictions with experimental results. It is shown that the model can accurately predict block trajectories and block velocities for rockfall analysis with and without drapery.

1. Introduction

The rockfall hazard in areas such as mountainous regions, quarries and mines needs to be rigorously managed. This is essential in order to avoid fatalities, damage to infrastructure and production losses. Preventing all rockfall events is almost impossible, but the installation of rockfall protection systems is a common and effective way to control the hazard.

Rockfall protection systems can be classified as either active or passive [1]. Active systems, such as rock bolts, anchors and grouted bars, are used to prevent instability from occurring. Passive systems, such as ditches, embankments and fences, are designed to control the dynamic motion of the blocks. Drapery systems can be considered as systems that are somewhere in between active and passive systems [1]. Simple mesh drapery systems or unsecured draperies consist of flexible wire meshes draped over the rock surface and usually just anchored along the top of the slope [2]. The drapery covers the extent of the initiation zone of rockfall prone areas, but rocks can still detach and fall in between the mesh and the rock face. The purpose of the drapery is to blanket the slope and, therefore, to improve the stability of potentially unstable blocks and to control the path of falling blocks [3].

In Australian coal and metalliferous mines, draperies are commonly used to prevent rocks from impacting directly onto the concrete culverts which are used as portal structures for underground access [4,5]. However, blocks can still detach, fall in between the drapery and the rock slope and impact on the portals (or in their vicinity) at the bottom of the highwall. This represents a serious hazard since the portals are crucial for both surface and underground activities. Therefore, an accurate assessment of the residual rockfall hazard at the base of a highwall is of prime importance for the design of underground entries. These assessments are usually based on simple 2D rockfall modelling and some empirical assumptions for the frictional resistance of the drapery [5]. An accurate assessment would require a proper prediction of block trajectories and velocities, but no such tool is currently available.

Despite drapery systems having been used as rockfall protective measures for many years, it is only recently that their design has been addressed in the scientific literature. To date, the focus has been on experimental testing of single components [6] and on full-scale field testing [1,4,7]. Although several numerical models for restraining nets and net barriers have been presented in the scientific literature (see e.g. [8]), the modelling of draperies as a whole system has been addressed rarely. A study using shell finite elements in order to investigate the stress distributions in the mesh and the force distribution in the support structure of drapery systems was presented in [9]. The study showed that the

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self-weight of the mesh, the friction interface between the slope and the mesh, and the additional weight due to accumulated debris have a big influence on the system behaviour. In addition, it showed that reinforcements such as additional bolts and vertical ropes are essential to reduce the stresses within the mesh, whereas horizontal ropes provide no benefit. A similar model to evaluate the maximum forces in the support structure, but using truss elements, was presented in [10,11]. This model considers the impact of the blocks on the drapery, but it does not properly consider the slope. The block can interact only with the mesh. Recently, a more advanced model was presented using a special purpose finite element code [12]. The latter was used to model a rockfall attenuating system including ground contact where the slope was simplified to a homogeneous infinite plane and the block was able to interact with the mesh and the slope. All these studies were based on the finite element method (FEM), but applications with the discrete element method (DEM) can also be found in the scientific literature where the mesh is modelled by spherical particles [13–15]. A discrete model for a double-twisted hexagonal mesh was presented in [16]. The authors in this paper mention that their model could be applied to wire meshes draped over a cliff face. However, an application to a real drapery system was not shown. To the authors' knowledge, a model representing the full complexity of a drapery system has not yet been presented in the scientific literature.

This paper presents a novel approach for simulating rockfalls behind drapery systems which can be used to assess the residual rockfall hazard involved with such systems. The work is based on the experimental study on rockfall drapery systems for open-pit highwalls presented in [4], and the results of this study are used to calibrate and validate the numerical model presented. The first part of the paper gives a short introduction to DEM numerical modelling and the basic contact models that are used throughout this work. The second part gives a detailed description of the rockfall model without drapery. The representation of the slope as well as the block–slope interaction model are discussed. Simulations without drapery are carried out, and the numerical predictions are compared to experimental results in order to calibrate the model. The third part of the paper focuses on the modelling of rockfalls with drapery. The representation of the drapery and the block–drapery and slope–drapery interaction models are discussed. Simulations with drapery are carried out and the numerical predictions are compared to experimental results in order to calibrate and validate the model. The final part of the paper shows how the newly developed model can be applied to accurately assess the residual rockfall hazard at the base of a highwall. Simulations without and with drapery are carried out using representative blocks and the efficiency of the drapery is assessed. To the authors' knowledge, this is the first time that a numerical model for predicting the residual rockfall hazard, with drapery installed, has been presented in the scientific literature. It should be noted that the approach is not only limited to mining applications, but is also suitable for civil engineering problems.

2. DEM numerical modelling

Rockfall phenomena involving drapery systems are complex dynamic problems which include large deformations and complex contact conditions, as well as interactions between different materials (e.g. block–slope, block–drapery and slope–drapery) and material failures (e.g. failure of the mesh and fragmentation of the block). The DEM is able to handle such dynamic problems very well, and the open-source framework YADE [17,18], which is based on the classical DEM [19], is used in this paper.

2.1. General DEM concept

The DEM implemented in YADE allows finite displacements and finite rotations of discrete bodies, which interact with each other, to be considered. As in the classical 3D DEM, only spherical particles are considered to be fully dynamic. This results in more efficient contact detection and easier implementation. Arbitrary shapes can still be approximated by an assembly of spherical particles where particles can either be bonded or clumped together [20]. The motion of the particles is governed by the equations of rigid body dynamics (Newton's second law). An explicit time stepping algorithm is used to solve these equations for each dynamic particle involved in the simulation. New contacts are automatically updated during the calculation process and the corresponding contact forces are applied. The interactions between the particles are considered explicitly and relatively simple contact laws are used to calculate the contact forces. Interacting particles can overlap and the contact forces are defined as a function of this overlap. The time step and the contact properties have to be chosen so that the overlap stays small during the simulation, i.e. the overlap should be smaller than the radius of the smallest particle involved. Fig. 1 illustrates the concept of normal overlap for two interacting spheres and for a sphere interacting with a smooth non-dynamic (fixed) boundary.

2.2. Basic contact model

The contact model relates the relative displacement (or overlap) to the contact force **F** acting at the contact between two interacting particles. The contact force **F** has a normal component F_n and tangential component F_t. The normal contact model consists of a linear spring model. Hence, the normal contact force F_n is calculated from the relation

$$F_n = k_n u_n \tag{1}$$

where k_n is the normal contact stiffness and u_n is the relative normal displacement between the interacting particles. The normal spring is only active in compression, i.e. when the particles overlap, and no tensile forces are generated. The incremental tangential contact force ΔF_t is linked to the incremental tangential displacement Δu_t as follows:

$$\Delta F_t = k_t \Delta u_t \tag{2}$$

where k_t denotes the tangential contact stiffness between the interacting particles. The total tangential force F_t is updated incrementally in each time step. A Coulomb-like slip model is applied in the tangential direction, which means that F_t is limited in magnitude as follows:

$$|F_t| \le |F_n| \tan \varphi \tag{3}$$

where φ corresponds to the internal friction angle. A schematic representation of the normal and tangential interaction law is

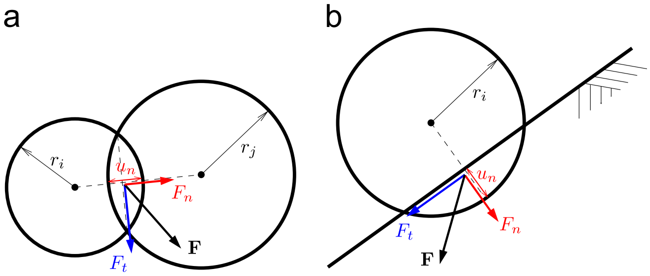

Fig. 1. Concept of overlap and contact force: (a) between two spheres with radius r_i and r_j and (b) between a sphere with radius r_i and a smooth boundary.