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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.

Keywords: Discrete element method (DEM), 3D rockfall modelling, Double-twisted hexagonal mesh, Rockfall protection, Full-scale modelling

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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 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, 14, 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 and 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 as well as 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.

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.

2.2. Basic contact model

The contact model relates the relative displacement (or overlap) to the contact force $\mathbf{F}$ acting at the contact between two interacting particles. The contact force $\mathbf{F}$ 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:

$$F_n = k_n u_n \quad (1)$$

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:

$$\Delta F_t = k_t \Delta u_t \quad (2)$$

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:

$$|F_t| \leq |F_n| \tan \varphi \quad (3)$$

where φ corresponds to the internal friction angle. A schematic representation of the normal and tangential interaction law is shown in Fig. 2a and b, while the corresponding rheological model is shown in Fig. 3a.

3. Development of a 3D discrete rockfall model

3.1. Representation of the slope

An accurate representation of the slope is fundamental in order to perform a realistic rockfall simulation. Hence, a realistic 3D representation of the highwalls considered

Fig. 2. Schematic representation of the contact law: (a) for normal interaction and (b) for tangential interaction.

Fig. 3. Rheological model and its parameter: (a) for block/slope-drapery interaction and (b) for block-slope interaction.

in the experimental study presented in [4] is created. The multi-view reconstruction approach presented in [21] is used in this work.

The method belongs to a recent series of new photogrammetry methodologies emerging from computer vision research which allow non-conventional image block geometry (see e.g. [22]). The images, obtained using a common “off-the-shelf” digital camera and without following a specific sequence, can then be automatically processed. The result is a high resolution geo-referenced 3D point cloud, with sub-pixel accuracy (the position of a point is derived from several pictures rather than just two), of the object of interest [23].

The automatically generated point cloud is treated using advanced 3D mesh processing tools (e.g. MeshLab [24]) to obtain a representative triangulation of the area

of interest. Finally, the triangulated surface is imported into YADE, where a lithology and material properties (e.g. coefficients of restitution) are assigned to each triangle. In the present work, the method is applied to two sections of the highwall, described in detail in [4], and identified respectively as “Site 1—drapery” (Fig. 4) and “Site 2—no drapery” (Fig. 5).

Figs. 4a and 5a show, respectively, the point clouds obtained using the aforementioned multi-view reconstruction approach for the two sections. Figs. 4b and 5b show the point clouds considered for the analysis of the two areas of interest, and Fig. 4c and 5c the two models obtained from the triangulation process. The model of “Site 1—drapery” has an average of about 13 triangles per m^2 , and its height and width are, respectively, 39.5 m and 25.9 m. A total of 18,372 triangular elements are used to represent the slope and the zone at the base of the highwall. The model of “Site 2—no drapery” has a total of 20,081 triangular elements, with an average number of triangles per m^2 of about 12. The height of the model is 53.1 m and its width is about 19.5 m.

Table 1

Normal coefficients of restitution e_n used in this work (cf. [4]).

Material	e_n	
	“Site 1—drapery”	“Site 2—no drapery”
Sandstone (sandst)	1.00	1.00
Mudstone (mudst)	0.61	0.59
Mudstone debris (muddebri)	0.11	n/a
Sandstone/Mudstone (interb)	0.71	0.61
Mudstone/Siltstone (mudsilt)	0.93	n/a
Coal	0.41	0.41
Debris	0.22	0.13

(a)

(b)

(c)

Fig. 4. Highwall representation of “Site 1—drapery”: (a) dense point cloud, (b) decimated point cloud and (c) triangulated surface for the model (colours indicate different materials).

(a)

(b)

(c)

Fig. 5. Highwall representation of “Site 2—no drapery”: (a) dense point cloud, (b) decimated point cloud and (c) triangulated surface for the model (colours indicate different materials).

3.2. Block–slope interaction

A proper description of the impact of the block on the highwall requires capturing the block–slope interaction, which is a complex phenomenon. It involves energy diffusion associated with wave propagation within the slope, as well as energy dissipation due partly to friction and material fragmentation [8].

A simple model to account for energy dissipation uses the so-called “coefficients of restitution” (see e.g. [25, 26]). These are usually calculated as the ratio between the velocity before and after rebound, and characterise the decrease in velocity and the loss of energy upon impact. Typically, their value is determined from back analysis or field experiments (see e.g. [27, 28]). In the following, the concept of coefficients of restitution is adapted for the DEM.

The slope is represented by non-dynamic (i.e. fixed) triangular elements as previously described in Section 3.1. The concrete block is represented by a rigid assembly (clump) of uniform spheres with a radius of 2 cm and an overlap of 2 cm as shown in Fig. 6a. These latter seem to be reasonable for a realistic representation of the roughness of the block used in the experimental tests in [4]. The same value was used in the model presented and calibrated in [15]. The interaction between block and slope is represented by interactions of spheres with non-dynamic triangular elements. The concept shown in Fig. 1b is used for the overlap.

A main feature of the block–slope interaction is that energy must be dissipated upon impact. Different contact laws have been presented in the literature in order to consider this energy dissipation (see e.g. [29]). In this work, viscous damping is used to dissipate energy during the impact phase and the basic contact model introduced in Section 2.2 is extended by adding a damping element in the normal direction (Fig. 3b). Only damping in the normal direction is considered and energy in the tangential direction is dissipated via friction, which is already included in the basic contact model. Eq. (1) for the block–slope interactions becomes

$$F_n = k_n u_n + \alpha \frac{du_n}{dt} \quad (4)$$

Fig. 6. Block representation with uniform spheres with a radius of 2 cm and an overlap of 2 cm: (a) EOTA block and elongated/platy blocks (b) D_{90} and (c) D_{100} .

where α denotes the viscous damping coefficient and $\frac{du_n}{dt}$ the relative normal velocity between the particles in contact. The damping coefficient α can directly be related to the normal coefficient of restitution e_n and is given by the following relation (cf. Eq. (2.9) in [30])

$$\zeta = \frac{\alpha}{\alpha_{\text{cr}}} = \frac{-\ln e_n}{\sqrt{\pi^2 + \ln^2 e_n}} \quad (5)$$

where ζ is the damping ratio and α_{cr} is the critical damping coefficient. The critical damping coefficient α_{cr} is defined as

$$\alpha_{\text{cr}} = 2\sqrt{k_n \hat{m}} \quad (6)$$

where k_n indicates the normal contact stiffness and $\hat{m}$ is the effective mass of the two colliding particles with mass m_1 and m_2 given by

$$\hat{m} = \frac{m_1 m_2}{m_1 + m_2} . \quad (7)$$

For the block–slope interaction, the mass corresponding to the slope, e.g. m_2 , can be assumed as infinite, and Eq. (7) simplifies to

$$\hat{m} = m_1 \quad (8)$$

where m_1 is the mass of the particle in contact with the triangular element of the slope.

It should be noted that the linear force law in Eq. (4) leads to a normal coefficient of restitution in Eq. (5) that is independent of the impact velocity. This behaviour is not observed in experiments, nonetheless, it is a warrant assumption for the purpose of the current study. A more detailed discussion on this issue can be found in [30].

3.3. Results and discussion

The experimental tests T07–T13 [4] carried out at “Site 2—no drapery” are used to validate the 3D rockfall model. During the experimental program concrete blocks were released from two positions on the highwall, indicated as B1 and B2 respectively. Four blocks were released from position B1 (T07–T10) and three blocks were released from position B2 (T11–T13). Both initial positions are highlighted in Fig. 7. The normal coefficients of restitution, which are principal input parameters for the block–slope interaction, were calculated from the data obtained during the tests [4]. Their mean values are used in this work and are listed in Table 1. The normal and tangential contact stiffnesses and the local friction angle are assumed to be the same for all materials on the highwall. This simplification is made in order to limit the number of parameters which have to be calibrated. Furthermore, additional information would be necessary to calibrate the parameter for each single material. The time step for all the simulations is set to $\Delta t = 2\text{e-}5\text{ s}$ which corresponds to a fraction of the critical time step identified in [15].

The influence of the contact parameters k_n , k_t and φ is investigated by a series of simulations with different sets of parameters and by comparing the numerical results to the experimental ones. For each set of parameters, seven rockfall simulations are performed, releasing the block from seven different positions corresponding to small

variations of the experimental positions B1 and B2. Such variations are indeed necessary to reproduce some variability in the numerical results. Horizontal shifts of 2 cm parallel to the highwall are arbitrarily chosen for that purpose.

Several indicators derived from the trajectories of the blocks obtained in [4] are then used for comparison of the numerical and experimental results. These indicators include the number of impacts on the wall (final impact not included) and the location where the final impact occurs, the travel time t_{fin} until the final impact, and the absolute translational and angular velocities v_{fin} and ω_{fin} at the final impact. The final impact is to be understood as the impact at the base of the highwall. It can occur on the debris accumulated at the base of the highwall or in the mud depression located at the bottom of the highwall. The experimental results are summarised in Table 2. The main findings of the parametric study are summarised in the following paragraph and the results showing the best agreement with the experimental results are discussed in detail.

The local friction angle φ appears to have only a minor influence on the numerical predictions. This can be attributed to the fact that the highwall is very steep, with a dip of about 70–75°. A local friction angle of $\varphi = 30^\circ$ is subsequently used for all simulations. The stiffness parameters k_n and k_t have some influence on the trajectories but no real tendency can be observed. The best agreement between the numerical and experimental trajectories is obtained with $k_n = 1\text{e}6 \text{ N/m}$ and $k_t/k_n = 0.05$. The results are summarised in Table 3, where the positions B1.1–B1.3 and B2.1–B2.2 correspond to the variations of positions B1 and B2, respectively. A good agreement is observed by comparing the mean values (MEAN) and standard deviations (STDEV) of the experimental and numerical results shown in Table 2 and Table 3 respectively. In both the experimental results and numerical predictions, two impacts occur on the wall on average. The mean values for the travel time t_{fin} and the translational velocity v_{fin} are very similar, although the numerical model slightly overestimates the translational velocity and, hence, gives shorter travel times. The biggest disagreement between the experimental and numerical results can be observed for the angular velocity. However,

these results also have the biggest variability in both cases as can be seen from the standard deviations. In addition, the numerical results predict an impact in the last layer of sandstone for position B1.3 (see Fig. 7a) which results in a very high final angular velocity. No impact on this layer was recorded during the experiments, but the numerical value for the angular velocity before the impact on the sandstone layer is similar to the one measured in the experiments.

Fig. 7a shows a comparison between the trajectories recorded during the experiments and the trajectories calculated by the 3D DEM model. A reasonably good agreement can be observed. Fig. 7b summarises the main numerical results by showing the trajectories coloured according to the absolute translational velocity.

Table 2

Summary of main experimental results for “Site 2—no drapery” (cf. [4]).

Test	Position	Final impact on ^a	No. of impacts on wall ^b	t_{fin} [s]	v_{fin} [m/s]	ω_{fin} [1/s]
T07	B1	debris	2	3.5	28.4	20.3
T08	B1	mud	3	4	24.8	58.4
T09	B1	debris	2	3.4	28.2	16.3
T10	B1	debris	2	3.6	28.1	24.8
T11	B2	mud	2	3.9	25.7	52.8
T12	B2	mud	2	4	25.5	48.4
T13	B2	debris	2	4.2	24.4	25.1
MEAN			2.1	3.8	26.4	35.2
STDEV			0.3	0.3	1.6	16.1

^a Final impact on debris or mud, whichever occurs first

^b Final impact not included

Table 3

Summary of main numerical results for “Site 2—no drapery”.

Position	Final impact on ^a	No. of impacts on wall ^b	t_{fin} [s]	v_{fin} [m/s]	ω_{fin} [1/s]
B1	mud	3	3.8	28.2	64.3
B1.1	mud	2	3.8	28.3	88.3
B1.2	mud	2	4.1	28	82.9
B1.3	mud	2	4.0	25.9	135.6
B2	debris	2	2.9	28	20
B2.1	debris	1	3.2	28.5	19.6
B2.2	debris	1	3.2	28.5	19.7
MEAN		1.9	3.6	27.9	61.5
STDEV		0.6	0.4	0.8	41.2

^a Final impact on debris or mud, whichever occurs first^b Final impact not included

4. 3D rockfall modelling with drapery

4.1. Drapery representation

The drapery installed on the highwall and described in the experimental work carried out in [4] consists of a Maccaferri double-twisted hexagonal wire mesh of the type 80 × 100 with a wire diameter of 2.7 mm. The same mesh was part of the numerical study in [15] and, hence, their mesh characteristics and properties are adopted for this work.

The steel wire mesh is represented by a set of spherical particles located at the physical nodes of the mesh. Remote interactions, i.e. interactions with no physical contact between the particles, are introduced to represent the wires between the nodes. The single wires and double-twists are defined by the initial geometry of the mesh (Fig. 8a). The wires are not discretised explicitly but their mechanical behaviour is

Fig. 7. Results for “Site 2—no drapery”: (a) comparison of trajectories for experimental (red) and numerical (blue) results and (b) trajectory with absolute velocity v from numerical analysis.

considered via the remote interaction model. The constitutive behaviours of the single wires and double-twists are defined on the basis of experimentally obtained stress–strain relations. In the numerical model these relations are approximated by piecewise linear functions (Fig. 8b). By using the inter-particle distance (i.e. wire length) and the defined cross-sectional area, the piecewise linear stress–strain curves are then transformed into force–displacement relations. These relations define the contact law of the remote interactions. Fig. 8c shows a schematic representation of the contact law. The model considers tensile forces only, since it is assumed that these are much higher than compressive forces because of the potential buckling effect. The contact stiffness upon loading changes with the wire elongation, whereas the stiffness upon unloading corre-

sponds to the initial elastic stiffness. When a certain limit is reached (marked by the cross in Fig. 8c), the wire breaks, and the corresponding remote interaction is lost. Finally, the model is extended in order to take global mesh characteristics into account, such as distortions of the wires and hexagons. A stochastically distorted contact model with two parameters is used which stochastically modifies the contact law, i.e. the force–displacement curve (Fig. 8d). The first parameter, λ_u , defines a horizontal shift to the force–displacement curve and the second parameter, λ_F , defines the stiffness of the wire in the shifted area. Energy dissipation due to local bending of the wires, which is not included in the current wire model, is taken into account by introducing non-viscous local damping. The damping coefficient used in this work is $\lambda_d = 0.02$. A detailed description and validation of the numerical model of the wire mesh can be found in [15].

4.2. Block/slope–drapery interaction

The drapery is represented by spherical particles as discussed in the previous section. Hence, the interaction between the block and the drapery consists of the interactions of spheres with other spheres (Fig. 1a), while the interactions between the slope and the drapery comprise interactions of non-dynamic triangular elements with spheres (Fig. 1b). The interactions are modelled by using the basic contact models introduced in Section 2.2.

4.3. Rockfall simulations with drapery

4.3.1. Positioning of drapery

Two preliminary steps are needed in order to simulate a rockfall behind the drapery. First, the particles representing the drapery are generated and aligned to the highwall. The model of the drapery consists of 112,502 particles which are positioned in a plane parallel to the highwall. Second, a simulation with gravity is carried out where all particles of the drapery, except the ones in the top row (red particles in Fig. 9c), are allowed to move. The particles can now touch the slope and interact with its triangular elements. The simulation is stopped when static equilibrium is reached. Fig. 9a and b

show the drapery in its final equilibrium condition. This condition is saved and used as the initial condition for all subsequent simulations. In the latter, the block is inserted at its position and released (Fig. 9c).

It should be mentioned that, in reality, the drapery is anchored on top of the highwall at a location which is a few meters from the edge [4, 5]. However, the mesh above the releasing position did not move during the experiments and, therefore, it is not considered in the numerical analysis. The drapery in the numerical model ends about 1 m above the releasing position of the block as can be seen in Fig. 9. Furthermore, the drapery installed on the highwall consists of four 4 m wide mesh panels which are laced together with rings and form a 16 m wide rockfall netting. However, the netting was installed in 2004 and its shape has changed significantly over the years. The current width of the drapery at the release position of the block is just about 12 m. This is the initial width considered in the numerical model. In addition, the netting is considered as one single panel.

4.3.2. Results and discussion

In the following, the experimental tests T01, T02 and T04–T06, presented in [4] and carried out at “Site 1—drapery”, are used to calibrate and validate the 3D rockfall model with drapery. During the experimental program, all concrete blocks were released from position A. In the numerical analysis, only one block is released from position A and the other four blocks are released from four different positions in order to introduce some variability. The new positions correspond to an arbitrarily chosen variation of position A. Horizontal shifts parallel to the highwall of 5 and 10 cm to the left and right of position A are used in this case. The parameters for the block–slope interaction are set according to the values identified in Section 3.3, and the normal coefficients of restitution from the experiments carried out at “Site 1—drapery” are used (Table 1). The contact properties for the slope–drapery interaction are $k_n = 1\text{e}5\text{ N/m}$, $k_t/k_n = 0.15$ and $\varphi = 30^\circ$, whereas the contact properties for the block–drapery interaction are $k_n = 1\text{e}5\text{ N/m}$ and $k_t = 0$. The tangential contact stiffness for the block–drapery

interaction is set to zero (i.e. only normal contact forces are considered) in order to avoid additional tangential interlocking forces. In practice, the block has smooth faces and the mesh is made of continuous wires, but in the numerical model both are represented by spherical particles and this will indeed generate some interlocking forces.

Similar indicators to those used in Section 3.3 are derived from the trajectories in order to validate the model. As for the results without drapery, the number of impacts on the wall (final impact not included), the travel time t_{fin} until the final impact, and the absolute velocities v_{fin} and ω_{fin} are used for comparison. The final impact corresponds to the impact on the debris on top of the portal at the base of the highwall. In the case of the simulations without drapery, the values for v_{fin} and ω_{fin} are equal to the maximum values. This is not the case for the simulations with drapery and, therefore, a distinction between maximum values along the highwall and values for the final impact is necessary.

Fig. 10a shows a comparison of the trajectories for all tests where trajectories from the experimental and numerical results are plotted in red and blue respectively. It can be seen that the predicted trajectories agree reasonably well with the experimental trajectories. Fig. 10b shows a plot of the absolute translational velocity along the trajectory from the numerical simulations.

Tables 4 and 5 summarise the experimental and numerical values which are used in the comparison. Generally, very good agreement is observed when comparing the mean values (MEAN) and standard deviations (STDEV). However, it seems that the numerical model underestimates the values for the final velocities v_{fin} and ω_{fin} . When looking at the velocities at the final impact on the debris on top of the portal, it can be seen that almost all numerical values for both v_{fin} and ω_{fin} (the corresponding values in Table 5 are indicated with a superscript b) are lower than the experimental ones. Fig. 11a shows the interaction of the block with the drapery for the fall along the slope, which looks very realistic. However, discrepancies occur when the block approaches the free boundary of the drapery at the bottom of the highwall, where the velocity of the block decreases abruptly. This effect varies with the trajectories, but can be observed

in all simulations as illustrated in Fig. 11c. Further investigations suggest that this discrepancy is related to limitations in the numerical model of the mesh. In particular, the model considers normal forces only and neglects the bending stiffness, which results in the mesh model being too flexible.

The simplification appears to properly model the fall along the slope, and to have a minimal influence in simulations A3 and A4 where the effect starts at less than 1 m from the boundary. The effect is slightly bigger for simulation A and A1, where it starts at about 1.5 m from the boundary. A major influence is observed for simulation A2, where the effect starts already at about 4 m from the boundary. The reason for the effect in all the simulations is that the free end of the drapery almost completely envelops the block as can be seen in Fig. 11b. This generates too many contact forces which restrain the block. Similar observations were made in [10] where truss elements were used to model the mesh. The behaviour cannot be corrected by changing the parameters used in the numerical simulation. Hence, the velocities of the block just before the effect starts are considered in the following.

The comparison between the experimental (Table 4) and numerical results (Table 5) shows a very good agreement. The mean value for the final translational velocity is almost the same (11.9 vs. 11.4 m/s), while a slightly bigger difference is observed for the mean value of the final angular velocity (23.6 vs. 27.3 1/s). In addition, it can be seen that the numerical model predicts an average of three impacts on the wall, whereas the experiments show one more.

The values for the maximum velocities $v_{\max}$ and $\omega_{\max}$ along the highwall agree very well with the experimental results. This result corroborates the model and the observations of the previous paragraphs. As in the case for the simulations without drapery, the travel time until the final impact is slightly underestimated by the numerical model. Overall, it can be seen that all values obtained in the numerical simulations are very similar to the values obtained in the experiments.

Table 4

Summary of main experimental results for “Site 1—drapery” (cf. [4]).

Test	No. of impacts on wall ^a	t_{fin} [s]	v_{fin} [m/s]	ω_{fin} [1/s]	v_{max} [m/s]	ω_{max} [1/s]
T01	4	3.9	11.8	12.3	13.7	29.0
T02	4	4.2	14.5	16.1	14.5	29.0
T04	4	4.1	12.1	34.5	14.9	53.8
T05	4	4.1	11.5	36.5	14.8	53.9
T06	5	4.1	9.4	18.5	16.5	41.9
MEAN	4.2	4.1	11.9	23.6	14.9	41.5
STDEV	0.4	0.1	1.6	10.0	0.9	11.1

^a Final impact not included

5. Rockfall scenarios with representative blocks

The numerical model developed in the previous sections is now used to investigate the residual rockfall hazard at the base of the highwall of “Site 1—drapery” for a more realistic scenario. The same highwall was part of the rockfall hazard study presented in [31], where discrete fracture network analyses were combined with kinematic analyses in order to identify shape and size distributions of unstable blocks. Results of the study showed that 90% of the unstable blocks had a volume of $V_{90} = 0.004 \text{ m}^3$ and that the maximum volume of an unstable block was $V_{\text{max}} = 0.115 \text{ m}^3$. Following a classification by [32], it was shown that the majority of the unstable blocks could be categorised as elongated and elongated/platy [5]. This is taken into consideration in order to generate two representative blocks, D_{90} (Fig. 6b, $0.06 \times 0.14 \times 0.5 \text{ m}^3$) and D_{100} (Fig. 6c, $0.18 \times 0.42 \times 1.52 \text{ m}^3$), and to simulate a more realistic rockfall scenario.

The scenario consists of a block of sandstone detaching from underneath an existing ledge in the sandstone layer on the top of the highwall. By assuming a density of

Table 5

Summary of main numerical results for “Site 1—drapery”.

Position	No. of impacts on wall ^a	t_{fin} [s]	v_{fin} [m/s]	ω_{fin} [1/s]	v_{max} [m/s]	ω_{max} [1/s]
A	3	3.7	10.2 / 8.8 ^b	43.7 / 38.4 ^b	14.5	66.6
A1	4	3.8	9.9 / 8.7 ^b	28.9 / 20.8 ^b	13.8	55.7
A2	3	3.4	14.1 / 8.8 ^b	31.8 / 11.2 ^b	15.2	64.2
A3	3	3.8	11.2 / 9.8 ^b	9.5 / 7.6 ^b	13.4	47.8
A4	3	3.7	11.4 / 9.7 ^b	22.6 / 23.7 ^b	13.7	46.3
MEAN	3.2	3.7	11.4 / 9.2 ^b	27.3 / 20.3 ^b	14.1	56.1
STDEV	0.4	0.1	1.5 / 0.5 ^b	11.2 / 10.8 ^b	0.6	8.3

^a Final impact not included^b Velocity without considering the correction due to the effect of the free boundary

sandstone of 2,400 kg/m³, the blocks D_{90} and D_{100} have a mass of 10 kg and 276 kg respectively. Simulations without and with drapery are carried out in order to assess the efficiency of the currently installed system.

Five release positions of the blocks are used for the simulations. Position 3 is located in the middle of the drapery. The remaining positions are varied horizontally along the highwall with a distance of about 2 m between each position. This means the blocks are released along a width of 8 m. The width of the drapery at the height of the release positions is about 10 m. All blocks are released separately.

Fig. 12a and Fig. 13a show the trajectories and absolute translational velocities for the simulations without drapery whereas Fig. 12b and Fig. 13b show the trajectories and absolute translational velocities for the simulations with drapery. The information relevant for a hazard assessment at the base of the highwall is summarised in Table 6 and includes the maximum velocities along the highwall v_{max} and ω_{max} , the final velocities

v_{fin} and ω_{fin} , and the horizontal distance d_{fin} measured from the base of the highwall at the top of the portal to the final impact point on the debris. The latter is very important, since it usually defines the length of the portal and the positions of the rockfall berms, whereas the final velocities are used to design the portal structure. The maximum velocities indicate whether the maximum values are reached either during the fall on the highwall or at the final impact.

It is noted that the effect observed in Section 4.3, where the free end of the drapery influenced the results of the final velocities because the drapery almost completely envelops the blocks, has little influence on the simulations presented in this section. This can be attributed to the shape and size of the representative blocks used in the simulations compared to the block used in the simulations of Section 4.

From Table 6 it can be observed that the absolute translational velocity v_{fin} at the final impact is reduced in all cases by the drapery. However, blocks released from position 1 and 5 show a very small decrease in velocity. Similar observations are made for the horizontal distance d_{fin} . In both cases the blocks have almost no interaction with the drapery. Indeed, the blocks slip sideways through the drapery in the first half of their travel and, hence, do not interact with the drapery thereafter. This indicates that unstable blocks located at about 1 m from the lateral boundary of the mesh may not be retained by the drapery. By looking at the trajectories of the scenarios of position 1 and 5, it can be seen that there is almost no difference between the trajectory without and with drapery, except for position 5 of block D_{100} . In this case, the trajectory changes because the initial interaction with the drapery keeps the block closer to the wall as in the case without drapery. This results in an additional impact in the Mudstone/Siltstone layer. The horizontal distance d_{fin} just increases in this specific case, whereas it is the same for position 1 of block D_{90} and decreases in all the other cases.

The absolute angular velocity ω_{fin} is reduced in most of the cases and increases in some cases because of additional impacts on the wall (D_{90} position 2 and D_{100} position 4). The maximum absolute translational and angular velocities are the same as the final ones in the case of no drapery. This is not the case for the simulations with drapery,

where the maximum values occur along the highwall, since the drapery reduces the velocities before the final impact occurs.

Fig. 14 summarises the main results for the residual rockfall hazard assessment at the base of the highwall. The results are plotted in terms of two reduction factors R_v and R_d . These factors indicate the reduction, due to the drapery, for the absolute translational velocity v_{fin} (Fig. 14a) and for the horizontal distance from the base of the highwall d_{fin} (Fig. 14b), respectively. In both cases it can be seen that almost no reduction takes place for blocks released at positions 1 and 5. As previously mentioned, this is due to the fact that the block could not be fully retained by the drapery.

Fig. 14a shows that the decrease in velocity for positions 2–4 of block D_{90} is consistently around 60%. The decrease in velocity for block D_{100} is less consistent. Positions 3 and 4 show a decrease of 55% and 43%, respectively, while position 2 shows a decrease of 20% only. The mean value for positions 2–4 indicates a decrease in velocity of around 60% for D_{90} and 40% for D_{100} .

From Fig. 14b it can be seen that the decrease in the horizontal distance for positions 2–4 of block D_{90} is around 80–90%. The decrease for block D_{100} again has more variation with positions 2 and 4 indicating a decrease of 80% while position 3 has a decrease of 30%. The mean value for positions 2–4 indicates a decrease in horizontal distance of around 90% for D_{90} and 65% for D_{100} .

It can be concluded that the drapery is more efficient in reducing the horizontal distance from the base of the wall than the absolute translational velocity of the final impact. Both results indicate a bigger variability for block D_{100} , whereas the results for block D_{90} are very consistent. Furthermore, the results show that the drapery is more efficient for block D_{90} . Indeed, the decrease in velocity and horizontal distance for block D_{90} is in both cases about 20% higher than for block D_{100} .

6. Conclusions

This paper presents a novel numerical approach for the modelling of rockfalls without and with drapery, based on the discrete element method. In the model, the highwall

was represented by triangular elements which were generated from a 3D geo-referenced point cloud obtained from a multi-view reconstruction approach. The different material layers of the highwall were identified and the corresponding material properties were assigned to each triangular element. The blocks released from the top of the highwall were represented by a rigid assembly of uniform spheres. Thus, the interaction between the block and the slope was represented by interactions of triangles and spheres. The energy dissipation upon impact was considered via normal viscous damping and friction. Normal coefficients of restitution were used to derive equivalent normal viscous damping coefficients. The drapery was represented by spherical particles generated at the physical nodes of the mesh. Remote interactions were introduced to simulate the wire behaviour, which was approximated by using a piecewise linear stress–strain curve. The experimental results presented in [4] were then used to calibrate and validate the numerical model.

Firstly, rockfall simulations without drapery were presented. Contact parameters for the block–slope interaction model, such as the contact stiffness in the normal and tangential direction and the local friction angle, were adjusted to best reproduce the experimental results. A comparison of the trajectories showed a reasonably good agreement. The main focus was on absolute translational velocities before the final impact on the debris or mud at the base of the highwall. Although the numerical model slightly overestimates the translational velocity, this can be attributed to the rather simple block–slope contact model implemented at this stage. However, mean values of the experimental results and numerical predictions were in good agreement.

Secondly, rockfall simulations with drapery were presented. Contact parameters for the block/slope–drapery interaction model, such as the contact stiffness in the normal and tangential direction and the local friction angle, were adjusted to best reproduce the experimental results. A comparison of the trajectories showed a good agreement between the experimental and numerical results. The maximum velocities along the highwall could be reproduced very well, whereas the numerical model slightly underestimated the final velocities at the base of the highwall. Some further investigations

showed that this discrepancy is related to some limitations in the model of the mesh. The model neglects the bending stiffness of the mesh and this could cause problems at free boundaries where the mesh completely envelops the block. In most cases this effect was very small, and good results could be obtained. Even better results were obtained by considering the value of the velocity just before the effect started.

Finally, the model developed in this paper was used to simulate realistic rockfall scenarios with representative blocks and to assess the residual rockfall hazard at the base of the highwall of “Site 1—drapery”. Two different blocks were released from several positions, and the results of the simulations without drapery were compared to the simulations with drapery. It was shown that the drapery was more efficient in reducing the horizontal distance from the base of the highwall than the absolute translational velocity of the final impact at the base of the highwall. In both cases, the decrease was about 20% bigger for the smaller block (D_{90}). This indicates that the drapery might not be very efficient for big blocks. Furthermore, it was shown that if the block detaches too close to the lateral boundary of the drapery, the block could slip sideways through the drapery and cannot fully be restrained. It should be noted that the effect of the free boundary, which was observed in Section 4.3, was not observed for the simulations with the representative blocks. This indicates that the effect not only depends on trajectory and velocity, but also on block shape and size.

It can be concluded that the presented numerical model gives good estimates for values of impact velocity at the base of highwalls and for values of horizontal distance of the final impact from the base of the highwall, for cases with and without drapery. Consequently, the residual rockfall hazard, i.e. after a drapery is in place, at the base of a highwall can be assessed and the concrete structures used as underground entries can be designed more efficiently. Furthermore, the model can be used to assess the efficiency of a drapery and to identify blocks which need to be pinned (e.g. with rock bolts) if they are not restrained by the drapery system.

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(a)

(b)

(c)

(d)

Fig. 8. Wire model: (a) location of particles and remote interaction model for the double-twisted hexagonal wire mesh, (b) stress-strain relations used in the model, (c) contact law and (d) distorted contact law.

Fig. 9. Position and boundary conditions for block drapery: (a) front view, (b) side view and (c) close-up view showing the block at its release position.

Fig. 10. Results for “Site 1—drapery” (drapery not shown): (a) comparison of trajectories for experimental (red) and numerical (blue) results and (b) trajectory with absolute velocity v from numerical analysis.

Fig. 11. (a) Block–drapery interaction during the fall and effect of free boundary of the drapery at the base of the highwall: (b) block enwrapped by the mesh particles and (c) plot of vertical coordinate z vs. absolute translational velocity v .

Fig. 12. Trajectories with absolute velocity v for D_{90} : (a) simulations without drapery and (b) simulations with drapery.

Fig. 13. Trajectories with absolute velocity v for D_{100} : (a) simulations without drapery and (b) simulations with drapery.

Table 6Summary of main numerical results for the simulations with blocks D_{90} and D_{100} .

Block	Position	v_{fin} [m/s]		ω_{fin} [1/s]		d_{fin} [m]		v_{max} [m/s]		ω_{max} [1/s]	
		no drap.	drap.	no drap.	drap.	no drap.	drap.	no drap.	drap.	no drap.	drap.
D_{90}	1	22.5	22.4 ^a	23.7	23.7 ^a	1.4	1.4 ^a	22.5	22.4 ^a	37.5	23.7 ^a
	2	22.9	8.7 / 8.3 ^b	19.1	22.0	3.7	0.3	22.9	9.5	19.1	95.0
	3	22.5	8.7 / 8.5 ^b	35.1	19.1	2.4	0.5	22.5	12.1	35.1	86.0
	4	22.7	8.4 / 8.1 ^b	12.9	8.7	2.5	0.2	22.7	11.4	12.9	80.3
	5	22.7	21.4 ^a	7.5	28.3 ^a	2.0	1.0 ^a	22.7	21.4 ^a	7.5	28.3 ^a
D_{100}	1	24.0	23.3 ^a	6.4	4.9 ^a	8.5	7.5 ^a	24.0	23.3 ^a	6.4	11.2 ^a
	2	21.3	17.1 / 16.9 ^b	40.4	11.7	3.2	0.6	21.3	17.1	40.4	41.1
	3	21.8	9.5 / 9.5 ^b	10.1	8.9	4.1	2.9	21.8	14.6	10.1	31.1
	4	22.8	13.0 / 12.5 ^b	8.5	21.3	9.1	1.6	22.8	17.8	8.5	35.6
	5	22.4	18.2 ^a	4.0	11.6 ^a	1.8	12.9 ^a	22.4	18.2 ^a	4.0	26.9 ^a

^a Block could not be retained by the drapery^b Velocity without considering the correction due to the effect of the free boundary

(a)

(b)

Fig. 14. Plot of reduction factors for positions 1–5 (superscript a indicates that the block could not be retained by the drapery): (a) for the final velocity and (b) for the horizontal distance from the base of the highwall.