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Numerical investigation of rockfall impacts on muckpiles for underground portals

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Abstract Small scale waste rock piles or muckpiles are commonly used as energy absorption barriers in various surface mining applications. This paper numerically investigates the impact behaviour of blocks on muckpiles used as cushion layer on top of underground portal entries. A three-dimensional discrete element model is implemented into the open-source framework YADE and validated using full-scale experimental data. The model allows estimating the energy absorption capacity of the muckpile and the impact forces acting on the portal structure. It also provides valuable information on the rebound characteristics which are useful for the definition of the potential safety areas in the vicinity of an underground entry. In order to show its capabilities, the model is applied to a large number of cases representing potential design conditions. The influence of block mass, impact velocity and absorbing cushion thickness on the forces at the base of the muckpile and the rebound trajectories after impact are investigated.

Keywords Discrete element method (DEM) · Numerical modelling · Granular material · Energy dissipation · Rockfall · Mining

1 Introduction

Muckpiles are small scale waste rock piles used as energy absorption barriers in various surface mining applications. They are used as rockfall protection berms along haul roads and highwalls and energy absorption layers for rockfall impacts on top of portals for underground entries (Fig. 1). Muckpiles play a crucial role in the safety of a mine site as they help to safeguard personnel and machinery working at the base of highwalls, protect portals from damage, and limit any potential financial losses should the production be stopped for safety issues (Giacomini et al. 2012). A proper understanding of the behaviour of a muckpile upon rock impact is critical for the design of an underground portal and the definition of the potential safety areas in the vicinity of the underground entry. However, despite their wide use, no specific design guidelines or methods are currently available and the actual energy absorption capacity of a muckpile is not known. Little research has been conducted on their design and construction, mainly because of the technical issues related to the complicated nature of physical testing and the huge variability of the materials from which they are built. In the context of Australian coal mining, waste rock materials contain fines, gravels, cobbles and rocks or boulders of various sizes. As such they are generally characterised as granular materials (Fityus et al. 2008). The particle size can range from a few millimetres to metres, and the particles are usually characterised by sharp and angular shapes (Saxena et al. 1984; Barton 2008).

In the last 20 years, several experimental (Labieuse et al. 1996; Heidenreich 2004; Beladjine et al. 2007; Ammi et al. 2009; Schellenberg 2009) and numerical (Calvetti et al. 2005; Bourrier et al. 2008; Plassiard 2008; Watanabe et al. 2011) studies have been conducted to investigate the behaviour of granular materials upon dynamic impact with focus on the energy absorption capacity of cushion layers for infrastructures protection against rockfall.

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Fig. 1 Muckpile on top of a portal for an underground entry.

These studies provided useful insights for the design of rockfall mitigation measures such as cushion layers for rockfall galleries, gabions, sandwich structures and rockfall embankments (Schellenberg 2009; Labiouse et al. 1996; Watanabe et al. 2011; Calvetti et al. 2005; Plassiard 2008). However, to the authors' knowledge, none of these studies investigated the efficiency of muckpiles as a rockfall protective system in the mining environment. Calvetti et al. (2005) numerically studied the impact of a block on a shelter covered by an absorption cushion layer of gravel-like material using the commercial three-dimensional (3D) discrete element software PFC3D. A linear-elastic and a Coulomb-like contact law were used to model the normal and tangential contacts respectively, but the model did not consider any rolling resistance. Instead, the particle rotation was prevented, i.e., the rotational degrees of freedom were fixed, in order to obtain more realistic results. Additionally, the contact stiffness was defined as a function of the depth of the absorption layer to improve the propagation time of the wave transmitted in the layer upon impact. The numerical results reproduced the behaviour of the granular soils well in a quantitative sense. Nevertheless, the impact forces and wave propagation time were slightly overestimated and the stresses at the bottom plate were somewhat underestimated. The study highlighted the influence of the thickness of the gravel-like layer on the stress propagation mechanism within the absorption layer. However, one of the main limitations of the proposed model resides in the fact that spheres only were used to represent the cushion layer and the rotational degrees of freedom were fixed which is not realistic. More recently, Bourrier et al. (2008) implemented a two-dimensional discrete element model of a boulder impacting a layer of coarse granular soil in PFC2D to investigate the physical mechanism that governs the impact behaviour. In this case, the granular material was modelled using spheres and elongated clumps of particles to better simulate blocks of different shapes, and the non-linear Hertz-Mindlin contact model was used. The model, calibrated and validated using reduced-scale laboratory tests, showed that the shape of the particles in the impacted layer strongly influences the transmission of stresses within the layer. It also evidenced that the rebound of the block and the deformation of the layer upon impact are mainly related to the block size and the thickness of the impacted layer. Similarly, Plassiard (2008) and Plassiard and Donzé (2010) looked at the penetration depth and maximum impacting force on a granular rockfall embankment upon block impact using the discrete element code SDEC. A linear hysteresis model was used for the normal contacts and a Coulomb-like model was employed for the tangential contacts between particles. The model accounted for the energy dissipation at impact through a normal viscous damping law, a damage law and a moment transfer law which allowed for more realistic predictions. The maximum impact force was identified as a function of impact energy, Young's modulus and slope orientation.

Muckpiles are not standardised rockfall protective structures, as the shape of the cushion layer and the particle size of the material can vary significantly depending on the mine geology and mine practice. Hence, numerical simulations can represent a valid tool to gather critical information, such as forces at the top of the concrete structure and block trajectories, to improve their design and assess the associated residual rockfall hazard. This paper uses the discrete element method (DEM) to gather this critical information. The first part of the paper presents a short introduction into the DEM and the contact models used throughout this work. The second part describes the influence of boundary conditions and various parameters on the proposed model. A mixture of spheres and clumps is introduced to model various sizes of particles constituting the waste rock material. The numerical results are compared to experimental observations in order to calibrate and validate the model. The final part of the paper presents a parametric study conducted to investigate the influence of the block size, the initial orientation of the block, the impact velocity (angular and translational) of the block and the muckpile geometry on the response upon impact. The results provide fundamental insights into the block trajectories for

various block sizes and different muckpile geometries. The forces transmitted to the portal structure which are relevant for the design of the portal are also evaluated.

2 DEM formulation

2.1 Overview

The impact of a block on a layer of granular material is a dynamic problem which includes large deformations and complex contact conditions, as well as interactions between different materials and failure mechanisms. In this work the DEM implemented in the open-source framework YADE (Kozicki and Donzé 2009; Šmilauer et al. 2010) is used to model the phenomenon. YADE is based on the classical DEM formulation (Cundall and Strack 1979) and, as such, it is able to handle dynamic problems very well. The fundamental assumption of the DEM is that the material consists of rigid, locally deformable particles. The DEM enables the consideration of finite displacements and rotations of interacting discrete bodies. These bodies can be approximated by an assembly of spherical particles that can either be bonded or clumped together (Donzé et al. 2009).

The following equations of rigid body dynamics govern the motion of the particles:

$$\mathbf{F}_i = m_i \ddot{\mathbf{u}}_i \quad (1)$$

$$\mathbf{T}_i = J_i \dot{\boldsymbol{\omega}}_i \quad (2)$$

where $\mathbf{F}_i$ is the resultant force acting on a particle i (e.g., gravitational force, contact forces), $\mathbf{u}_i$ is the displacement of the particle centroid, $\boldsymbol{\omega}_i$ is the angular velocity of the particle, m_i is the particle mass, J_i is the moment of inertia and $\mathbf{T}_i$ is the resultant moment acting on the particle.

Eqs. (1)–(2) are solved using an explicit time stepping algorithm for each dynamic particle involved in the simulation. New contacts are automatically detected and updated during the simulation process and the corresponding contact forces are applied. The particles are allowed to slightly overlap during collision and the contact forces are defined as a function of this overlap. As in the classical 3D DEM, only spherical particles are considered to be fully dynamic (each sphere has 6 degrees of freedom).

2.2 Contact model

In the present work a contact model similar to the one used in Plassiard and Donzé (2010) has been implemented into YADE. The model consists of a Coulomb-like contact law for tangential contacts and a linear model for normal contacts. In addition, two dissipative laws are introduced: non-linear normal viscous damping and a moment transfer law.

The linear model, is the basic linear elastic model proposed in Cundall and Strack (1979). The normal contact force F_n in the direction of the normal vector $\mathbf{n}$ (see Fig. 2a) is defined as:

$$F_n = k_n u_n \quad (3)$$

where u_n is the normal overlap, and k_n is the normal loading contact stiffness. The latter is defined as:

$$k_n = r \frac{K_n^A K_n^B}{K_n^A + K_n^B} \quad (4)$$

where K_n^A and K_n^B are the input values for the normal contact stiffness of the two interacting particles A and B respectively, and r corresponds to the mean radius associated to two interacting particles. The tangential contact is controlled via a Coulomb-like slip model. The incremental tangential contact force ΔF_t is linked to the incremental tangential displacement Δu_t as follows:

$$\Delta F_t = k_t \Delta u_t \quad (5)$$

where k_t denotes the tangential contact stiffness between the interacting particles. Similarly to the normal contact stiffness k_n , the tangential contact stiffness k_t is calculated as:

$$k_t = r \frac{K_t^A K_t^B}{K_t^A + K_t^B} \quad (6)$$

where K_t^A and K_t^B are the input values for the tangential contact stiffness associated to two interacting particles A and B respectively. The total tangential force F_t is updated incrementally at each time step. F_t is limited in magnitude since a Coulomb-like slip model is applied in the tangential direction as particles start to slide. The following equation is used to limit the total tangential force:

$$|F_t| \leq |F_n| \tan \varphi + c \quad (7)$$

where φ and c are the internal friction angle and internal cohesion of the granular material.

The non-linear viscous damping proposed by Plassiard and Donzé (2010) for the modelling of an impact of a block on an embankment is taken into account. A damping force F_n^d that opposes the relative velocity for the duration of the contact is added to the normal contact force F_n . Therefore, the normal contact force for the linear spring model of Eq. (3) becomes

$$F_n = k_n u_n + F_n^d \quad (8)$$

and F_n^d is calculated as

$$F_n^d = -\alpha (\bar{m} k_n)^{1/2} \left(\frac{u_n}{\bar{r}} \right)^{\frac{1}{4}} \dot{u}_n \quad (9)$$

where $\bar{m}$ and $\bar{r}$ are the mean mass and mean radius of the two bodies in contact and $\dot{u}_n$ is the relative velocity between two particles in contact.

Fig. 2 (a) Contact between two spheres A and B and (b) the relation between relative rotation and moment.

The moment transfer law is defined as an elastic-plastic spring model (Fig. 2b) without damping (Plassiard and Donzé 2010; Bourrier et al. 2013; Modenese 2013). Considering two spherical elements A and B (Fig. 2a), the relative rotation of the spheres Ω_{AB} is used to define rolling and twisting components. The twisting part of the relative rotation is defined as:

$$\Omega_{AB}^t = (\Omega_{AB} \cdot \mathbf{n}) \mathbf{n} \quad (10)$$

where the unit normal vector $\mathbf{n}$ of the contact between sphere A and B is:

$$\mathbf{n} = \frac{O_B - O_A}{\|O_B - O_A\|} \quad (11)$$

where O_A and O_B are respectively the position of the centres of sphere A and B. The rolling part of the relative rotation can then be calculated as:

$$\Omega_{AB}^r = \Omega_{AB} - \Omega_{AB}^t \quad (12)$$

and the elastic moment $\mathbf{M}_{elast}$ created by the rolling part becomes:

$$\mathbf{M}_{elast} = k_r \Omega_{AB}^r \quad (13)$$

where k_r is the rolling stiffness. The rolling stiffness k_r defines the level of rolling control and is calculated from the tangential stiffness as:

$$k_r = \beta_r \bar{r}^2 k_t \quad (14)$$

where β_r is the coefficient of rolling.

The rolling moment M_r is calculated as:

$$M_r = \min(\|\mathbf{M}_{elast}\|; |M_{plast}|) \frac{\mathbf{M}_{elast}}{\|\mathbf{M}_{elast}\|} \quad (15)$$

The elastic limit M_{plast} of the moment is defined as

$$M_{plast} = \eta_r \bar{r} |F_n| \quad (16)$$

where η_r is the dimensionless coefficient of the rolling elastic limit.

3 Experimental data and numerical representation

Experimental tests carried out by Giacomini et al. (2012) have been used to define the geometry and the initial conditions of the model. During the experimental campaign, EOTA-shaped (EOTA 2008) concrete blocks (Fig. 3b) with a maximum dimension, D (Fig. 3a), of 30 cm and a mass of 44.5 kg were released from the top of a coal mine highwall. The blocks fell between the highwall and a drapery rockfall protection system installed over the rock surface. At the end of their fall the blocks impacted on a layer of waste rock material (muckpile) which was positioned at the base of the highwall on top of an underground portal entry. Digital images were used to create a geo-referenced 3D model of the testing area in order to obtain an accurate 3D surface representation (Thoeni et al. 2014). During the tests, the motion of the blocks was recorded by a synchronised stereo pair of high-speed cameras. This allowed 3D block trajectories to be reconstructed and gave estimates of the block velocities. During the experimental campaign a translational energy at impact on the debris (muckpile) ranging between 1.7 and 14 kJ was measured on top of the portal (Giacomini et al. 2012).

Fig. 3 EOTA shaped block: (a) block dimensions, (b) block used during the experiments and (c) its numerical representation.

In the present work, the 3D geometry of the waste material positioned at the bottom of the test site impacted by the block at the end of its fall is used to model the muckpile. Experimental results showed that most of the impacts occurred in a small sector of the muckpile close to the highwall (Effeindzourou et al. 2015). This portion of the muckpile is numerically approximated by a triangular prism with a width W (Fig. 4a).

The block is modelled as a rigid assembly (a clump) made of spheres with a radius of 2 cm (Fig. 3c). One of the tests conducted by Giacomini et al. (2012) is chosen to set up the initial conditions of the block at impact. The translational velocities v in the xyz-axes are $v_x = 2.6$ m/s, $v_y = 0$ m/s and $v_z = -11.6$ m/s. The angular velocity ω in the xyz-axes are $\omega_x = 0$ rad/s, $\omega_y = 12.3$ rad/s and $\omega_z = 0$ rad/s. Finally, as shown in Fig. 4b, the initial orientation of the block at impact is equal to 40° which corresponds to the measured value (Giacomini et al. 2012). It represents the angle between the x-axis and the symmetry axis of the block.

Fig. 4 Muckpile model: (a) dimensions and (b) top view of the muckpile with initial orientation of the block.

The particle size distribution (PSD) of the muckpile material is characterised via indirect analysis conducted on representative digital images collected during the field experimental campaign (Fig. 5). The indirect PSD indicates a well graded material with particles varying from 2 mm to about 1 m in diameter. The bigger particles in the material indicate recently fallen blocks and are not representative of the muckpile material. Hence, additional direct and indirect analyses are also conducted on more representative samples of material collected on site to further investigate the particle shape.

In order to limit the computational time it is general practice in DEM to work with a reduced PSD (see, e.g., Utili et al. 2015; Watanabe et al. 2011). Therefore, a much narrower particle size distribution with the ratio of maximum to minimum particle size equal to 4 is used in the simulations with sizes ranging between 25 mm and 100 mm with aspect ratio ranging from 1 to 2 (Fig. 6).

Fig. 5 PSD curves associated to the experimental and numerical representation of the muckpile material.

Fig. 6 Characteristic muckpile material: (a) block shapes for particle size ranging between 25 mm and 100 mm, and (b) and (c) particle shapes and corresponding numerical approximation in white.

An analysis of the laboratory samples showed that even though the material has a huge variability the majority of the particles are characterised by a rounded and elongated shape (Fig. 6). Hence, it is decided to model the muckpile material with a mixture of spheres and clumps (or aggregates of spheres). The elongated particles are represented by an aggregate of two spheres allowing for a more realistic representation of the shape (Fig. 6b). The final muckpile assembly is generated as follows. First, an assembly using spheres only is created by gravity deposition in a box. No compaction is applied. The porosity of the muckpile is around 0.45. The same contact law is used for the sphere–sphere and sphere–box interactions. Similarly, the same parameters are used for both the sphere and the boundaries with the exception of the friction angle. Indeed, no friction is applied between the box and the muckpile material to limit the influence of the lateral boundary conditions. Then, interactions between two particles are identified in the sphere assembly. For a predefined percentage of these interactions, particles are randomly selected and bonded by an unbreakable link to form a rigid elongated aggregate. Particles in the aggregates may overlap slightly (note that the overlap is negligible compared to the size of the particles) but no contact forces are generated inside the clumps. In this way, a random distribution of clumps is obtained within the original sphere assembly. A percentage of 40% of clumps (based on the number of particles in the assembly) is used as it roughly corresponds to the percentage of elongated shapes observed in the laboratory sample.

4 Calibration and validation

In the following sections, the numerical model is first calibrated and then validated. The block, the muckpile geometry and the initial conditions of the block described in Section 3 are used in the analysis. The set of material parameters calibrated and validated for a generic gravel-like material by quasi-static and dynamic conditions proposed by Plassiard and Donzé (2010) is considered. The parameters are listed in Tab. 1. Only the main dynamic parameter, the normal viscous damping parameter α , is investigated in the following calibration. Thereby, the predicted rebound characteristics are compared to the one observed during the experimental test (Giacomini et al. 2012). In addition, the influence of the lateral boundary conditions, i.e., the width of the muckpile, is studied in order to minimise the computational costs. Finally, the algorithm for generating the random clump distribution

is validated by studying the influence of the spatial distribution of the clumps on the rebound of a block after its impact on a muckpile.

Table 1 Input parameters representing the generic granular material (from Plassiard and Donzé 2010).

Input Parameter	Value
Normal stiffness, K_n (MN/m ²)	170
Tangential stiffness, K_t (MN/m ²)	35
Local friction angle, μ (°)	17
Local cohesion, c (kPa)	20
Rolling coefficient, β_r (-)	1.8
Rolling elastic limit, η_r (-)	1.8

4.1 Influence of the lateral boundary conditions and calibration of viscous damping

The influence of the width, W , of the muckpile is investigated to optimise the muckpile geometry representation according to impact load diffusion and the computational costs. Montani Stoffel (1998) and Zhang et al. (2016) observed that the load on a cushion layer of granular material impacted by a block diffuses into the layer within a cone volume defined by an angle between 33° and 47°. According to the authors' observation, a load diffusion angle of 45° (associated with a width of the muckpile of $W = 2.5$ m) is used to characterise the reference lateral boundary conditions. Three values of W are considered: 1 m, 2 m and 3 m. The influence of the non-linear viscous damping parameter, α , is investigated using six values: 0 (no viscous damping), 0.1, 0.2, 0.5, 1 and 2, where the latter corresponds to the value used in Plassiard and Donzé (2010). The same initial particle assembly is used for the parametric study to maintain the arrangement of particles in the vicinity of the impact as suggested by Bourrier et al. (2008).

Results are shown in terms of the block trajectory and forces calculated at the base of the muckpile. Numerically, the base of the muckpile is defined as the bottom of the box containing the sphere/clump assembly. Normal and tangential translational coefficients of restitution as well as the angular coefficient of restitution upon impact, are also considered and calculated as the ratio of the post-impact velocity over the pre-impact velocity:

$$e_n = \frac{|v_n^{post}|}{|v_n^{pre}|} \quad (17)$$

$$e_v = \frac{|v_t^{post}|}{|v_t^{pre}|} \quad (18)$$

$$e_\omega = \frac{|\omega_{post}|}{|\omega_{pre}|} \quad (19)$$

where v_n^{post} and v_t^{post} are the normal and tangential velocity post-impact, v_n^{pre} and v_t^{pre} the normal and tangential velocity pre-impact, ω_{post} is the angular velocity post-impact, and ω_{pre} is the angular velocity pre-impact (Fig. 7).

The minimum and maximum values of the restitution coefficients measured by Giacomini et al. (2012) for the impact of the block on a debris of waste rock material at the bottom of the highwall are used for comparison: $e_n = \{0.13, 0.31\}$, $e_t = \{0.22, 0.57\}$ and $e_\omega = \{0.85, 1.75\}$ ($e = \{\text{minimum, maximum}\}$).

Fig. 8 shows the forces calculated at the bottom of the muckpile and the trajectories of the block for the three considered widths and the six values of viscous damping. The numerical results clearly show that an increase of the value of the damping parameter corresponds to an increase of force measured at the bottom. Also, the forces increase with increasing width. Nevertheless, forces predicted for the muckpile with widths of 2 m and 3 m are in a very similar range, with minimum peak forces of 83 kN and 99 kN and maximum peak forces of 121 kN and 126 kN for 2 m and 3 m respectively. This corresponds to an increase of the maximum peak force at the bottom of the muckpile of only 4%.

Furthermore, realistic trajectories are observed for viscous damping values higher than 0.2 for all the three widths. In particular, for $\alpha = 1$, a post-impact angle between 10° and 15° is observed, which is similar to the observed experimental value. Considering $\alpha = 1$ for the two muckpiles with width 2 m and 3 m also provided a good agreement between post impact block trajectories with a minor variation in the peak forces. Taking into account that the simulation time almost doubles when considering a width of 3 m instead of 2 m, and given the similarity between the predicted response upon impact between the muckpiles with width 2 m and 3 m, the model with width 2 m is considered a good compromise to gather accurate results at reasonable computational costs.

As an additional check, the variation of coefficients of restitution with the considered values of viscous damping and the three muckpile widths is presented in Fig. 9. Results are compared to the range of minimum and maximum values of restitution coefficients measured on site. According to the variation in trajectory shown in Fig. 8, it is observed that the damping parameter and the width of the muckpile significantly affect the monotonic evolution of the computed coefficients of restitution, in particular for values of $\alpha < 0.5$. As previously evidenced, a good compromise between block trajectory, computational costs and coefficient of restitution can be observed for $\alpha = 1$.

Fig. 7 Sketch of the investigated muckpile parameters.

Table 2 Characteristics of the blocks used during the simulations.

Block	Diameter D_e (cm)	Block mass (kg)
B1	20	15
B2	30	44.5
B3	40	100
B4	50	200

Table 3 Initial rotation of the block used during the simulations.

Initial rotation	Angle ζ ($^\circ$)
ζ_0	0
ζ_1	22.5
ζ_2	45
ζ_3	67.5

4.2 Influence of the spatial distribution of the clumps

The influence of the random spatial distribution of the clumps throughout the sphere/clump assembly is assessed by running eight simulations with different spatial distribution (Test 1 to Test 8). Each sphere/clump assembly consists of 60% of spheres and 40% of clumps (based on the number of particles in the assembly). The same initial granular assembly is used for the muckpile but the location of the clumps is varied randomly. The initial conditions of the block presented in Section 3 and the model parameters presented in Section 4.1 are used. Results are analysed in terms of effect of the random clump distribution on the force measured at the base of the muckpile and the block trajectory. Fig. 10 shows that the spatial distribution of the clumps has a negligible influence on both the block trajectory and the force measured at the base of the muckpile. In particular, the peak maximum force varies between a minimum of 105 kN and a maximum of 115 kN which represents a variation of less than 10%. The algorithm used to introduce the clumps in the sphere assembly does not considerably affect the results in terms of evolution with time of the force measured at the base of the muckpile and of the block trajectory.

5 Application

The model developed in the previous section is used to numerically investigate the influence of the block size (and block mass), its impact velocity (angular and translational) and initial orientation on the behaviour upon impact of the muckpile. A total of 432 unique simulations were performed. The effect of the muckpile geometry (i.e., the slope angle θ of the muckpile, Fig. 7) on its response upon impact is also examined. Tabs. 2–6 summarise the sets of parameters used during the proposed study. Four block sizes are used. Considering the block used in Giacomini et al. (2012) as the reference block, B2, with a maximum dimension $D = 30$ cm, three additional blocks are taken into account: a smaller block, B1, with a maximum dimension $D = 20$ cm, and two additional blocks, B3 and B4, with $D = 40$ cm and $D = 50$ cm, respectively.

Four values of the initial orientation of the block, ζ (Fig. 4b), are considered in the simulations. Starting with an initial rotation of 0° (ζ_0), the three supplementary values correspond to an increase of 22.5° each, up to a maximum of 67.5° (ζ_3).

Fig. 8 Influence of the width and the viscous damping coefficient α on the force at the bottom of the muckpile (a), (c), (e) and on the trajectory of the block (b), (d), (f).

Fig. 9 Influence of the width and the viscous damping coefficient α on the coefficient of (a) normal and (b) tangential restitution, and (c) the rotational coefficient of restitution.

Fig. 10 Influence of the spatial distribution of the clumps: (a) the force calculated at the base of the muckpile and (b) the trajectory of the block.

Table 4 Translational velocities before impact.

Translational velocity	v_x (m/s)	v_y (m/s)	v_z (m/s)	v_{pre} (m/s)	Drop height H (m)
v_1	2.26	0	-10	10.25	5
v_2	4.52	0	-20.00	20.50	21
v_3	6.78	0	-30.00	30.76	48

It is assumed that the block can impact on the muckpile with three different velocities, summarised in Tab. 4. These values are based on experimental data (Giacomini et al. 2012): v_1 corresponds to the impact velocity measured at the top of the muckpile during the first test of the experimental campaign, and v_2 and v_3 are the maximum velocity at impact on the highwall and at the bottom of the highwall respectively, measured during the tests conducted without drapery installed on the wall. v_3 represents the worst case scenario. The three velocities correspond to an equivalent (or potential) free-fall height, H , of 5 m, 21 m and 48 m respectively. The block's angular velocities obtained from Giacomini et al. (2012) are used and reported in Tab. 5.

The geometrical conditions at impact, such as the height of the impacted layer, h , the muckpile angle, θ , and the impact angle, ψ , with respect to the muckpile slope (Fig. 7) are given in Tab. 6.

For each block (or each maximum dimension D), a width of the muckpile equal to 2 m is used according to the preliminary study proposed in Section 4.1.

Table 5 Rotational velocities before impact.

Rotational velocity	ω_x (rad/s)	ω_y (rad/s)	ω_z (rad/s)	ω_{pre} (rad/s)
ω_1	0	0	10	10
ω_2	0	0	20	20
ω_3	0	0	40	40

Table 6 Slope angle used during the simulations.

Slope angle	θ (°)	Impact angle, ψ (°)	h (m)
θ_1	20	57	0.8
θ_2	25	52	1.1
θ_3	30	47	1.4

Fig. 11 shows the forces calculated at the base of the muckpile for each block (B1 to B4) for three equivalent falling heights $H = 5$ m, 21 m and 48 m, and three muckpile geometries ($\theta = 20^\circ$, $\theta = 25^\circ$ and $\theta = 30^\circ$). Numerically, the base of the muckpile is defined as the bottom of the box containing the sphere/clump assembly. As expected, the results show an increase in the peak force with an increase in the equivalent fall height for all three geometries. For all three geometries a mean reduction of the peak force of around 40% is observed for all four blocks when the equivalent fall-height is reduced from 48 m to 21 m. An additional decrease of the equivalent fall-height to 5 m, results in a decrease in the peak force of 62% in average with values ranging between 55% to 66%.

Results also evidence the influence of the increase of the impacted height h on the calculated forces: for example, for the block with the biggest mass, B4, an increase of h from 0.8 m to 1.1 m produces only a 2% reduction of forces, while an additional increase of 0.3 m (or increasing θ from 20° to 30°) induces almost a 30% reduction. This effect is also noticed for blocks B3 and B2, however a diminish of the influence of the height of the layer is also noted with a reduction of the block size.

Furthermore, the mass of the block also influences the impact time, defined as the time elapsed between the first and the last instant for which the forces on the bottom of the muckpile are greater than zero: the impact time varies between 0.012 s for block B1 to 0.022 s for block B4.

In Fig. 12, results are plotted in terms of the forces calculated at the bottom of the muckpile versus block size and impact energy for the three muckpile geometries ($\theta = 20^\circ$, $\theta = 25^\circ$ and $\theta = 30^\circ$). Data are shown for all the four blocks. For each block four initial rotations ζ (0° , 22.5° , 45° and 67.5°), three equivalent fall heights H (5 m, 21 m and 48 m) and three initial angular velocities ω (10 rad/s, 20 rad/s and 40 rad/s) are considered. The mean value of the peak force and its minimum and maximum values are given by point markers and bars respectively. For a given muckpile geometry, the peak force calculated at the base of the muckpile increases with both block size and impact energy. The force increases bi-linearly with the energy with a break of slope at around 20 kJ for all three cases. For every muckpile the variation of the forces as a function of the energy can be fitted using a bi-linear regression and the coefficient of determination R^2 shows a good approximation. Looking at the impact energies and the corresponding calculated forces at the bottom of the muckpile, it can also be noted that, for energies over 20 kJ, an evident reduction of peak force is given by the highest impacted height (h) (that correspond to $\theta = 30^\circ$): for impact energies of around 94 kJ, forces calculated at the base of the layer vary from around 1300 kJ to almost 950 kN.

Figure 13 shows the trajectories for each block (B1 to B4) in the x-z and x-y planes. For each block, two trajectories corresponding to the minimum and the maximum rebound height are displayed in the x-z plane. The horizontal distance from the end of the muckpile (i.e., $x = 3.44$ m and $z = 0$ m) to the intersection of the block trajectory with a horizontal plane ($z = 0$ m) is measured. This distance is referred as run out distance. Numerical results show that the trajectories of block B1 have the biggest dispersion for all three geometries. The horizontal distance between its trajectory and the horizontal plane at the bottom of the muckpile varies between 0.16 m to 6.7 m. The trajectories of block B1 are significantly influenced by the muckpile height and show a maximum run out distance ranging between 2.1 m to 6.7 m. Blocks B2–B4 are less affected by the muckpile geometry in their maximum rebound upon impact in the x-z plane with values varying from 2.1 m to 4.1 m for block B2, 1.1 m to 2.9 m for block B3 and 1.2 m to 4 m for block B4 for the three muckpile geometries. Similarly, the data shows that the smallest block, B1, is the most affected by the variation in impact height on its angle of deviation upon impact, χ , defined as the maximum angle between two trajectories of the same block on the xy-plane: the deviation angle reduces with increasing impact height of the muckpile, and reaches up to $\chi = 30^\circ$ for $\theta = 20^\circ$. This can partly be attributed to the fact that, for this smaller block, the size and arrangement of the particles of the muckpile material at the impact location have a much bigger influence on the rebound behaviour than for the bigger blocks (cf. Bourrier et al. 2008).

Numerical results highlighted two main aspects that should be considered for the design of a muckpile as rockfall mitigation measure on top of a portal: the maximum force measured at the base of the muckpile upon block impact and its run out distance after impact. Fig. 14a shows a diagram of the numerical forces measured on top of the portal versus the impact energy for all the three muckpile configurations. For the analysed cases,

Fig. 11 Predicted forces at the base of the muckpile for blocks: (a) B1, (b) B2, (c) B3, and (d) B4.

a negligible influence of the muckpile geometry on top of the portal could be observed for impact energies lower than 11 kJ.

Fig. 14b shows the predicted maximum run out distance measured from the top end of the portal versus the block size. For the four sizes of blocks considered, a higher variability in the maximum run out distances could be observed for blocks with a block size of 0.2m whereas for a block size higher than 0.2m, the influence of the muckpile geometry on the maximum run out distance diminishes. This suggests that in a preliminary design phase both impact energies and block sizes should be taken into account to identify the muckpile characteristics that comply to the expected energy and provide a safe working area in the portal vicinities.

6 Conclusions

A numerical model of the impact of a boulder on a muckpile of waste rock materials was developed using the open-source framework YADE. The muckpile material was represented by a mixture of spheres and clumps made out of two particles. The model was calibrated and validated using full-scale experimental data. The calibration of the model allowed the identification of contact parameters which permit a realistic reproduction of the experimental results. In addition, the calibration permitted to investigate the influence of the viscous damping and the width of the muckpile on the behaviour of the muckpile upon block impact. The results showed that the viscous damping influenced the block trajectory post-impact as well as the force calculated at the base of the muckpile. Nevertheless, it had a minor influence on the coefficients of restitution. The forces were also affected by the width of the muckpile. In fact, they increased with increasing width. This highlighted that when simulating a reduced model it is essential

Fig. 12 Summary of forces calculated at the base of the muckpile for (a) $\theta = 20^\circ$, (b) $\theta = 25^\circ$, and (c) $\theta = 30^\circ$.

Fig. 13 Summary of trajectories of the blocks in the x-z and x-y planes for (a) $\theta = 20^\circ$, (b) $\theta = 25^\circ$, and (c) $\theta = 30^\circ$.

to study the influence of the boundary conditions. The study of the width also allowed finding a compromise between accuracy and calculation time. The literature suggested a width of 2.5 m. Simulations performed with 2 m and 3 m showed similar results and hence the final study was performed with a width of 2 m. It was also shown that the algorithm to generate the random spatial distribution of the clumps is robust as it has little influence on the results.

The capabilities of the numerical model were then presented by performing a series of analyses of possible rockfall scenarios. The calibrated model was used to numerically investigate the influence of the muckpile geometry, block size (block mass) and block impact velocity (or equivalent free-fall height) on the forces transmitted at the bottom of the muckpile and on the block trajectories after impact. This investigation was conducted with the aim of providing useful information on the energy absorption capacity of muckpiles as rockfall mitigation measure which are positioned on top of concrete portal entries at the bottom of highwalls. In addition, the investigations of the rebound trajectories after impact allow the determination of the extent of the safety areas positioned around the portal for working personnel. The numerical results indicate a decrease in the forces at the base of the muckpile with an increase of the thickness of the impacted layer of granular material. The application of the model to a given

Fig. 14 Summary of the results: (a) Energy vs. forces and (b) block size vs. run out distance.

muckpile geometry, chosen in agreement with full-scale experimental data, also showed that an increase in impact energy produces an increase of the peak force at the base of the muckpile. A bi-linear behaviour was observed between energy and forces with a break of slope at around 20 kJ for all geometries. The model also allowed the influence of block size on the rebound trajectories to be investigated. The numerical predictions indicate that smaller blocks tend to bounce longer horizontal distances and reach higher rebound heights. Additionally, their trajectories have a wider dispersion after the impact. This indicates that small blocks will define the extension of the safety zone around the portals, whereas the big blocks will define the maximum impact energy for the design of the concrete portal. The developed numerical model and the presented findings are useful for the prediction of the safety areas around portals and for the design of the concrete portal where muckpile waste rock material is used as an energy absorption layer.

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