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DEM MODELING OF ROCKFALL REBOUND ON PROTECTIVE EMBANKMENTS

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Abstract. Design of Rockfall Protection Embankments and estimation of their capacity to control the trajectory of rock boulders are complex issues, which give considerable room for research and improvement. A lack of detailed models for the simulation of block rebound in the embankment vicinity is mainly due to the large number of parameters that influences the phenomenon. Therefore, the evaluation of the embankment efficiency in satisfactorily acting on the block trajectory, as a function of the site characteristics and boulder kinematics, is still precluded to design engineers.

In the present paper, the open-source code YADE, based on a discrete element method (DEM), is used to model the bouncing of a rock block on the embankment face, while taking into account a certain number of parameters with influence on the impact.

By contrast with previously developed models (DEM, FEM or coupled approaches), the aim is here to propose a model with limited computation cost. In this purpose, the embankment is modelled as a membrane interacting with the rock block. The embankment body is not represented because it would require a large number of particles, and, consequently, a high computational time. Various elements implemented in YADE are used to model the embankment surface, with the aim of mimicking the mechanisms involved during the rock boulder rebound. The validity of the approach is addressed comparing simulation results with the few experimental data available from the literature. The influence of characteristics of the impacting block (radius and weight) and kinematic parameters (impact angle and velocity) on the restitution coefficients is explored. In particular, the normal (R_n), tangential (R_t) and energetic (R_{TE}) coefficients of restitution are monitored. The goal of defining an efficient model in a realistic range of these parameters is pursued.

1 INTRODUCTION

Rockfall protection embankments are massive civil engineering structures, built in elevation with respect to the ground to intercept large falling rocks. They are typically 3 to 7 m high and up to a few hundred meters long. On a functional point of view, the design of an embankment aims in assessing the ability of the structure in adequately modifying the blocks trajectories. This is particularly related to the way the blocks bounce on the embankment's face. Such a rebound appears to be extremely complex as it depends on many parameters related to the block shape, velocity (translational, rotational), to the impact point location and to the embankment characteristics (constitutive materials and geometry).

Different studies have addressed numerically the impact response of embankments (Peila et al. [10], Plassiard and Donzé [12], Breugnot et al. [2]). The block rebound and its post-impact trajectory have been investigated by Plassiard and Donzé only ([12]). It is worth highlighting that, as shown by Lambert et al. [7], simulation tools used by design engineers for modelling the trajectory of rock blocks down natural slopes are not appropriate for modelling the rebound after impact on rockfall protection embankments.

The purpose in this study is to create a model that can properly reproduce the block bouncing, accounting for the relative influence of each parameter, structural or mechanical. The main interest is to develop a model, inexpensive in terms of computational time, which permits a calibration as simple as possible. This model is developed using YADE [14], an open source software based on a discrete element method (DEM).

The impacted surface is modelled considering a physical idea and a design that strictly simulate the response of the real structure. Its body is not considered in the representation because of the large dimension and, consequently, large number of particles that would be required in the modelling, and the computational time. The model is calibrated and the response is verified using experimental data and empirical relations.

2 PHYSICAL MECHANISM

Embankments are designed in order to limit the there that the block jumps or rolls over the structure after bouncing on the structure face. This risk depends on many parameters.

It is increased if (1) the uphill face inclination is insufficient (inclination higher than 65° are sometimes recommended for avoiding any 'springboard effect'), (2) the block trajectory before impact is oriented upward and (3) the incident rotational velocity of the block is high. The shape of the block can influence its behaviour post impact: a shape with edges can favour bouncing over the structure while a spherical one will favour rolling over.

Bouncing also depends on the energy dissipation occurring in the embankment during the impact. The impact by the block induces a high stress in the vicinity of the impacted area, with compaction and particle crushing inducing energy dissipation. These mechanisms are associated to longer impact durations (up to 300 ms) depends on the embankment fill materials characteristics.

The developed model aims at proposing a tool to be used by design engineers and accounting for the influence of all these parameters on the post-impact trajectory of the block.

3 THE STRUCTURE

3.1 The model – Physical idea

The aim of this work is to develop a computationally-efficient model of the block rebound on embankments uphill face. The main mechanisms controlling the block-structure interaction are the penetration (in terms of force and deformation) and the friction at the block/face interface. It is proposed to model this interaction via a membrane located at the embankment face. This membrane is supported by simple mechanical systems as shown in Figure 1. This physical model is based on vertical elements supporting a surface with frictional characteristics. These elements can reflect a combined behaviour of springs, dampers, sliders, etc., simulating the overall structure's behaviour.

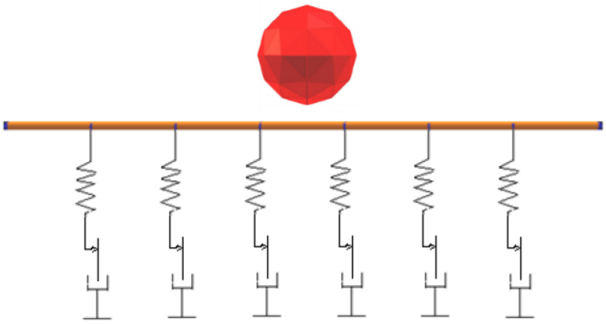

Figure 1: Physical model considered for the structure modelling.

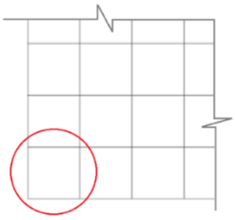

Figure 2: Scheme of the elementary structure (circled in red), reproduced to create the overall structure.

3.2 Model construction

The surface is built reproducing a square elementary structure (Figure 2). The surface's edges are blocked, in order to maintain the overall position of the surface in the modelling space during the impact. The vertical elements are calibrated in order to control the behaviour of the structure during the penetration.

Some points are crucial:

- The surface has to be large enough in order to avoid any influence of the boundary conditions on the block-surface interaction.

- The dimension of the elementary structure has to be small with respect to the radius of the impacting block, to ensure a contact as continuous as possible between these two bodies during impact. For this reason, a dimension of 1/5 the radius was chosen.
- The expected maximum penetration being 1.5 m, a length of the vertical elements of 2 m is used.

As for the surface mass, two cases have been tested: (1) constant surface mass, even changing the dimensions of the boulder and (2) surface mass proportional to the boulder mass. Simulations showed that the two cases led to the same maximum penetration values. However, an irregular behavior of the surface during deformation was observed when its mass was too high compared to the boulder mass. Some areas of the surface showed temporarily an unexpected and non realistic deformation. Therefore, choice was made to give the surface a mass proportional to the boulder mass.

The study of the penetration focuses on the impact moment having a duration typically less than 300ms. Gravity was not considered in the modelling, due to its very limited influence on the block trajectory over such a short period of time.

3.2.1 The elementary structure

The elementary structure is built using available elements from YADE: nodes (Grid Nodes), cylinders (Grid Connections), and PFacets.

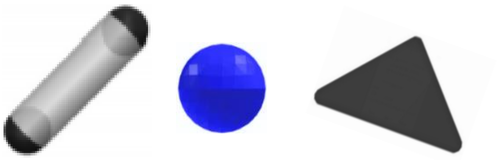

Figure 3: Elements of Yade - cylinders, spheres, Pfacets.

PFacets are used to manage the friction between the boulder and the surface. These were preferred over the so-called Facets elements, because these latter did not allow creating a continuous surface, due to discontinuities from one element to the other. This problem was overcome considering PFacets inside a triangular configuration between physical elements: nodes (Grid Nodes) in the angles, and cylinders (Grid Connections) connecting them. In this way the space between two of these elements in contact is occupied by the cylinders, which guarantee continuity in the structure.

Two different configurations for the elementary structure were tested (Figure 4). The elementary structure was created using 2 or 4 PFacets. In Figure 4, PFacets are the triangular elements, the Grid Nodes appear in yellow and the Grid Connections appear in orange. Using 4 PFacets an additional node is located in the structure centre and the radius of Nodes and Grid Connections is smaller than in the previous case.

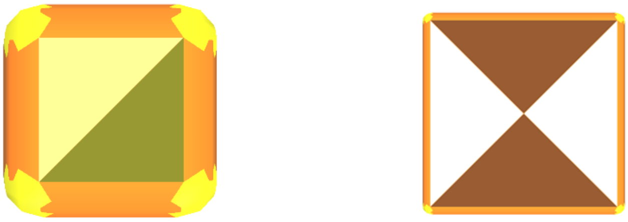

Figure 4: The two types of elementary structures tested (2 and 4 Pfacets, left and right, resp.)

The behaviour of the model with the first elementary structure resulted problematic. The response of the surface to the impact was not symmetric with respect to the impact point in case of a normal impact. This problem was attributed to the fact that the mass of PFacets is concentrated on the nodes at the edges of the triangle. In fact these elements were originally developed for fixed configurations, while in the proposed application these elements are mobile and experience large and fast displacements. The proposed solution to overcome this problem was to use the second type of elementary structure, with 4 PFacets.

In the case of the model built reproducing the second elementary structure, with 4 PFacets, the number of vertical elements is twice that of the previous case, because all the central elements of the elementary structures are clumped to vertical units. The overall surface is now symmetric with respect to each axis crossing the central node. Therefore, the response of this model to the impact is regular and symmetric.

4 ELASTO-PLASTIC MODEL

The membrane mechanical response to impact is mainly governed by the vertical elements, which response governs the penetration (including dissipation) and rebound. Vertical elements consist of Yade's elements named cylinders (Grid Connections) which were attributed the law developed by I. Olmedo et al. [9]. This interaction law allows the input of an elasto – plastic constitutive law, specifying parameters like the elastic deformation modulus, the deformation modulus in the plastic phase, or the unloading one, the yielding point (Figure 5). Nevertheless, these elements only work in tension, while it is supposed to work in compression in this application. As a solution, the trick consisted in placing these elements on the same side as the projectile (green lines on Figure 6) while making them invisible to the projectile so that there was no interaction between these two body types.

Each vertical element is connected, on one side to the surface thanks to a Clump with each Node of the elementary structures and to a fix point on the other side. In Figure 6, the boundary nodes of the surface are coloured in blue because these are fix compared to other nodes from the surface.

The parameters of these elements were calibrated, in combination with the characteristics of the surface, in order to have a response in terms of deformation vs the impact force as realistic as possible. The parameters reported in Table 1 were considered for the boulder and the embankment materials.

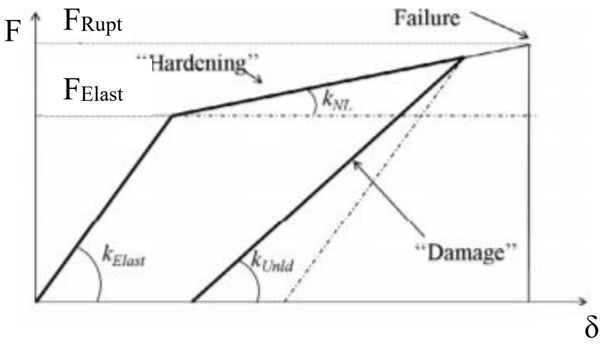

Figure 5: Scheme of the trilinear hysteresis.

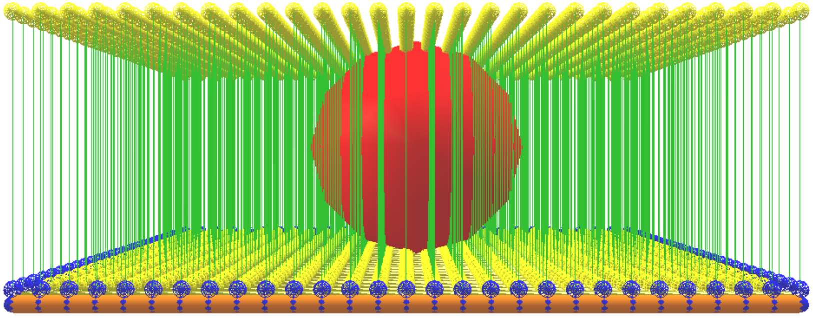

Figure 6: Overall structure (vertical elements in green).

Table 1: Model average parameters.

Young's Modulus [Pa]	4.00E+07
Poisson's Modulus [-]	0.3
Density [kg/m3]	2650
Friction Angle [°]	20

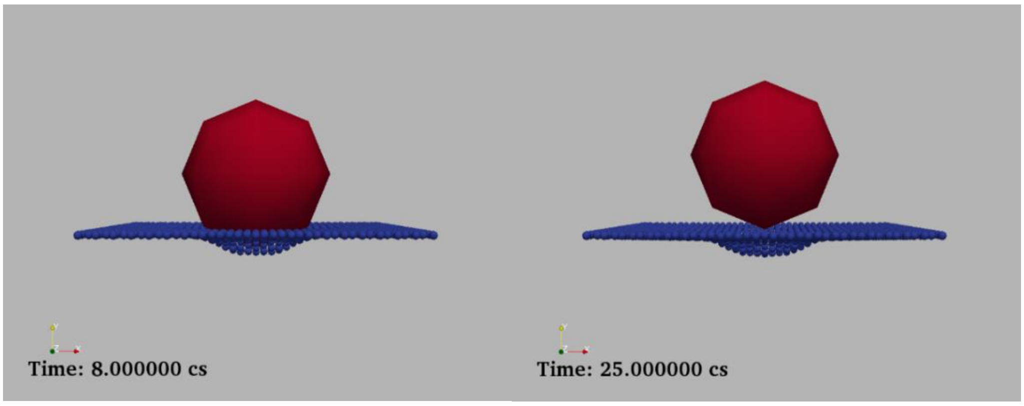

Figure 7: Impact simulation in the elasto-plastic model. Velocity of the rock block: (0,10,0) m/s.

4.1 Model calibration

The calibration was conducted with the aim of making the model able to approach realistic values for the penetration and impact force, considering existing knowledge from different sources. This calibration is not conducted for a specific study case. The values reported in Table 2 were used to calibrate the developed model, referring to an impact of a sphere 1 m in radius, and 11100 kg in mass, translational velocity perpendicular to the surface and rotational one null.

Table 2: Values used for the calibration of the model.

Boulder's velocity	10 m/s	25 m/s
Impact force	4000 kN	12000 kN
Max penetration	0.40 m	0.75 m
Duration	55 ms	45 ms

The maximum impact force was calculated by the Montani's equation [8].

$$F_i\ [kN] = 1.35 * exp\left(\frac{r}{3t}\right) * r^{0.2} * M_E^{0.4} * (tan\phi)^{0.2} * \left(m * H_c * \frac{g}{10^3}\right)^{0.6} \qquad (1)$$

With:

- r: radius of the projectile [m];
- t: soil layer thickness [m];
- M_E : impacted material static elastic modulus [kPa];
- ϕ : friction angle of the impacted material;
- m: mass of the projectile [kg];
- H_c : projectile free falling height [m];
- g: gravity [m/s].

Then the penetration was evaluated, using the simplified formulae:

$$p = \frac{mv^2}{F_i} \qquad (2)$$

The penetration was also compared to an equation derived from the work by Calvetti and di Prisco (2007) [3]:

$$p = 0.027 * r * v + 0.24 \qquad (3)$$

with *r* the radius of the impacting block and *v* its velocity.

Finally, the duration of the impact (penetration until the maximum value) was evaluated through the relation:

$$\Delta t = \frac{2mv}{F_i} \tag{4}$$

Regarding the penetration, it was decided to consider an average value between the values calculated from Montani’s, and Calvetti and di Prisco’s relations.

5 MODELLING APPROACH RELEVANCY

The model was tested varying the boulder’s radius, impact angle, and impact translational and rotational velocity with aim of assessing the relevancy of the proposed modeling approach in mimicking the block rebound.

Maximum penetration trend - impacts perpendicular to the surface

The first comparison concerns impacts perpendicular to the surface, varying the impact velocity. Calvetti and di Prisco [3] established trends between the maximum penetration and the projectile free falling height, considering different values of boulder’s radius. The application case was a concrete gallery covered with a granular layer from 1 to 2 meters, and an impacted by block of mass 850 kg. Based on numerical simulations, they proposed the chart presented in the Figure 8, on the left. A regular increase of the maximum penetration with the falling height is observed. Additionally, the slope of the curves increases with the boulder’s radii.

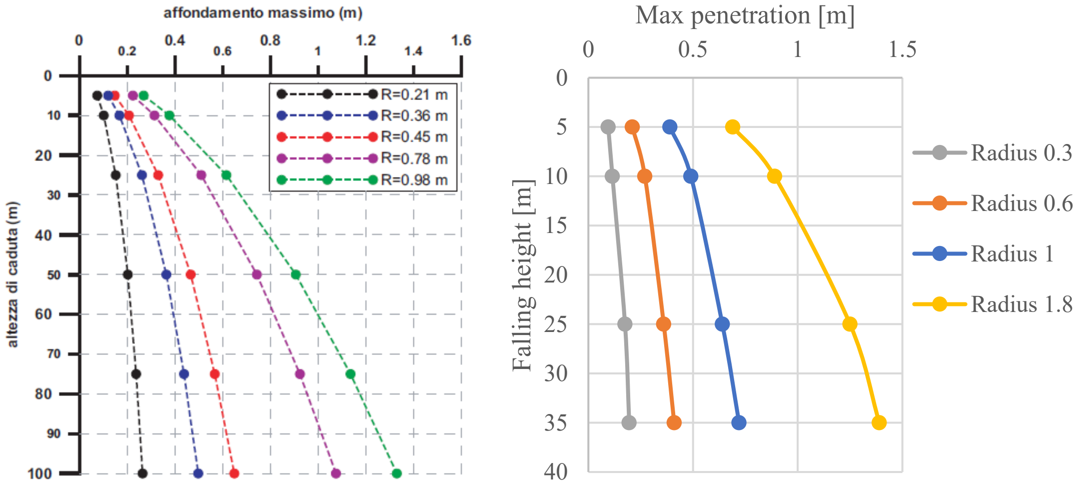

Figure 8: On the left, maximum penetration trend by Calvetti and di Prisco (2007) [3]. On the right, maximum penetration trend of the developed model.

In the developed model, the test was conducted in order to verify the regularity in the response of the system. Simulation results presented in the Figure 8, on the right, reveal similar trends. It means that, even though the model parameters were calibrated a rough way, the system reacts to the variations of the simulation conditions in a satisfactory way, varying the initial velocity and block radius.

Influence of the incidence angle and impact velocity

The model was then tested in the case of inclined impacts and compared with the state of the art and the experimental results presented in Heidenreich in 2004 [6] with the aim, again, at evaluation the relevancy of the modeling approach in reproducing established trends.

One way to study the rebound evolution with the incidence angle is to consider the normal, tangential and energetic coefficients of restitutions:

$$R_t = \frac{v_{t,r}}{v_{t,i}} \tag{5}$$

$$R_n = \left|\frac{v_{n,r}}{v_{n,i}}\right| \tag{6}$$

$$R_{TE} = \frac{E_{TOT,r}}{E_{TOT,i}} \tag{7}$$

$$R_\omega = \frac{\omega_r}{\omega_i} \tag{8}$$

Where:

- v_t and v_n: respectively tangential and normal components of the velocity;
- ω: angular velocity;
- “indices” i and r: incident and rebound elements, characterizing the velocity and the energy before and after the impact;
- E_{TOT}: total energy, sum of E_t and E_R, defined as

$$E_t = 0.5 * m * \left(v_x^2 + v_y^2\right) \tag{9}$$

$$E_r = 0.5 * \Theta * \omega^2 \tag{10}$$

With m the boulder mass, Θ the inertia moment and ω its rotational velocity (rad/s).

These coefficients allow quantifying the variation in the velocity components and the energy dissipation during the impact. Additionally, these restitution coefficients allow highlighting couplings between the different component of the generalized velocity vector (ex: After an inclined impact by a block without rotation, the rotational velocity is not null anymore).

The influence of the impact angle and the impact translational velocity (the rotational velocity, in this case, is imposed equal to zero) on the block rebound is studied considering two spheres, with radii of 0.3 and 1 m, and correspondent masses of 300 and 11100 kg. In this way, even the influence of the boulder’s mass, directly linked to the boulder’s radius, is showed.

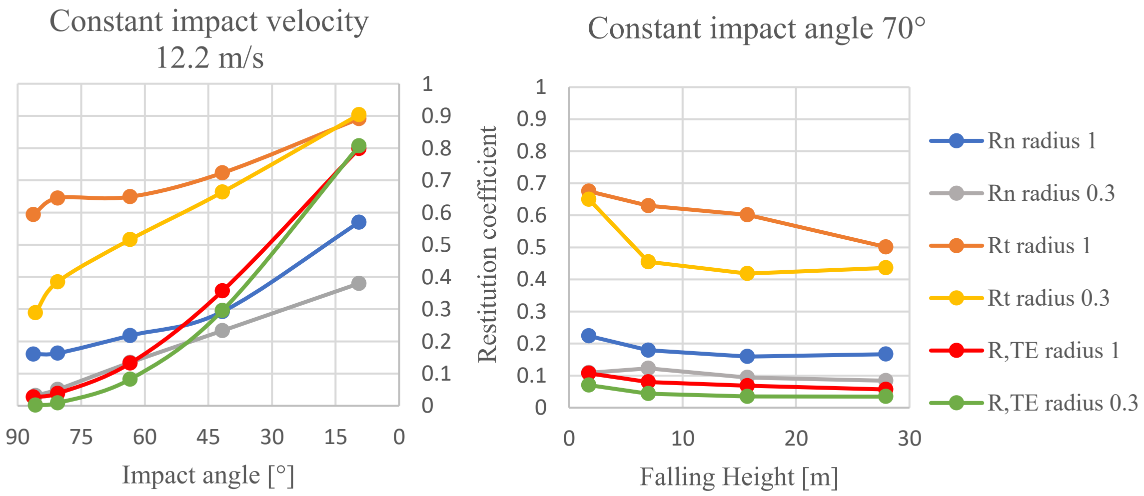

Figure 9: Influence of the impact velocity and the impact angle on the restitution coefficients.

In order to schematize the observations on the graphs, the trends are explained by arrows, indicating with the symbol ↗ an increasing, and with the symbol ↘ a decreasing.

➢ *Influence of the parameters related to the kinematics:*

- Maintaining the falling height constant (and, consequently, the impact velocity), and decreasing the impact angle

  R_n ↗, R_t ↗, R_{TE} ↗↗
- Maintaining the impact angle constant, and increasing the falling height (and, consequently, the impact velocity)

  R_n ↘, R_t ↘, R_{TE}↘.

  It is possible to observe an initial increasing of R_n for the block with a radius of 0.3 m.

➢ *Influence of the parameters related to the block:*

- Increasing the block radius and, therefore, the weight

  R_n ↗, R_t ↗, R_{TE} ↗

The trends may be compared to trends cited in the literature ([6]):

- Ritchie [13], in 1963, and Gerber [4], in 1995, basing on in situ observations, affirmed that the characteristics of the slope influence the blocks' kinematics. They observed that increasing the impact angle, the loss of energy becomes bigger.
- Habib [5], in 1977, declared that the normal coefficient of restitution is not only related to the ground material, but it is also a function of the block's kinematics, the mass and the shape.
- Bozzolo and Pamini (1986) [1], noticed that the R_{TE} depends on the impact angle: the energy dissipated rises with the growth of the impact angle, till a maximum value for an impact perpendicular to the surface.
- Pfeirrer and Bowen (1989) [11] perceived that faster blocks dissipate more energy than slower ones, during impact.

- B. Heidenreich (2004) [6] explained what happens during the impact: the translational energy decreases quickly, and the rotational one rises due to friction between block and slope.

  Additionally, B. Heidenreich observed that for falling heights between 5 and 10 m, R_t grows slightly with the coupled raise of mass and radius of the boulder. Even R_n shows a growing in this context.

  Finally, for increasing falling heights (so, impact velocities), she ascertained that R_t decreases greatly, while R_n and R_{TE} present, generally, a slower decreasing. In the half – scale experiments context (block with a radius of 0.3 m, in our case), she observed an initial increasing of the R_n with the falling height, that she justified in the way explained below. For small values of falling heights, the block rolling imposes the rebound direction (fairly tangential, so R_n results little, and R_t assumes a high value). For increasing falling heights, the growing slope ground resistance in front of the block provokes a more normal rebound, with respect to the slope (R_n initially rises, while R_t decreases strongly).

The comparison highlights that the trends from the model are consistent with test results obtained considering different experimental conditions.

Unfortunately, no real – scale data were available to check the behavior of the model considering a block radius of 1 m. However, in the hypothesis of good functioning of the system, that simulations would be useful to extend the study to more serious cases.

6 CONCLUSIONS

A simple block-soil interaction model has been proposed for modeling the rebound of rockfall on the uphill face of embankments. This simplified model relies on the substitution of the structure body by a surface, located on its impacted face, in order to save computation costs.

Different DEM strategies were considered for developing such a model using Yade's elements. The optimum consisted in a membrane made of the repetition of elementary structures made of 4 PFacets, supported by cylinder elements. The proposed model allows accounting for plasticity of soil associated to compaction and for friction at the block-surface interface.

A first comparison with previous studies confirmed the relevancy of the proposed modeling approach. In case of normal-to-the membrane impacts, observed trends concerning the penetration are in line with previously described ones. Varying the angle of incidence of the rock block also shows similar trends as those observed in the past. However, some limitations rose when addressing the influence of the block angular velocity (not shown here). Indeed, the latter appeared to have a moderate influence on the restitution coefficients, contrary to what was expected. This point will be improved.

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