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Simulation (2D and 3D) of randomization orbit and radius affected of rockfall on open pit mines

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ABSTRACT

Affected by rockfall, flyrock on pit walls with boundless energy makes an impact on the surface and the surrounding buildings near the open pit mines. These risks have studied by theoretical and experimental and determining the parameters and factors to simulating the orbit of fly rock and falling rocks. By empirical and simulation model of fly rock and rockfall, has made the risk of forecasting and proposed solutions to protected areas surrounding mine under slope cut.

1. Introduction

On the open pit mines, rockfall is the movement of rock from the slope that is steep the rock continues to move down the slope which may be by free falling, bouncing, rolling or sliding depending on the slope angle. Ritchie (1963) identifed the characteristics of rockfall motion relative to a slope's configuration and height, to determine the expected impact distance of a rockfall from the base of open pit benches (Pierson et al. 2001).

Irrespective of a rock's shape, the rock's mode of travel down the slope is a function of the slope angle. Figure 1(*b*) and an empirical design table of recommended minimum rock catchment area with and depth, based on the slope height and slope angle. Figure 1(*a*). Rocks fall in trajectory seldom give a high bounce after impact. Ritchie's study was based on data collected from rolling only a few hundred rocks. However, Ritchie's empirical table is still used by numerous state and local transportation agencies to dimension catchment areas. The major limitations of the Ritchie's design criteria always gives the same required catchment area width and height for a given slope height and slope ratio; rockfall's initial impact will be within the catchment area and only require some form of barrier on the road shoulder to keep vehicles from falling into the ditch and possibly overturning; rock rolling was done non-presplit highway and quarry slope and natural slopes. Rockfall starts with detachment of rocks from bedrock slope, which is cliff face in the case of a rockfall sources area. The degree of rockfall promotion depends on the environmental factors causing physical and chemical weathering, and on the bedrock type (Dorren, 2003).

After the rock has been detached and starts to

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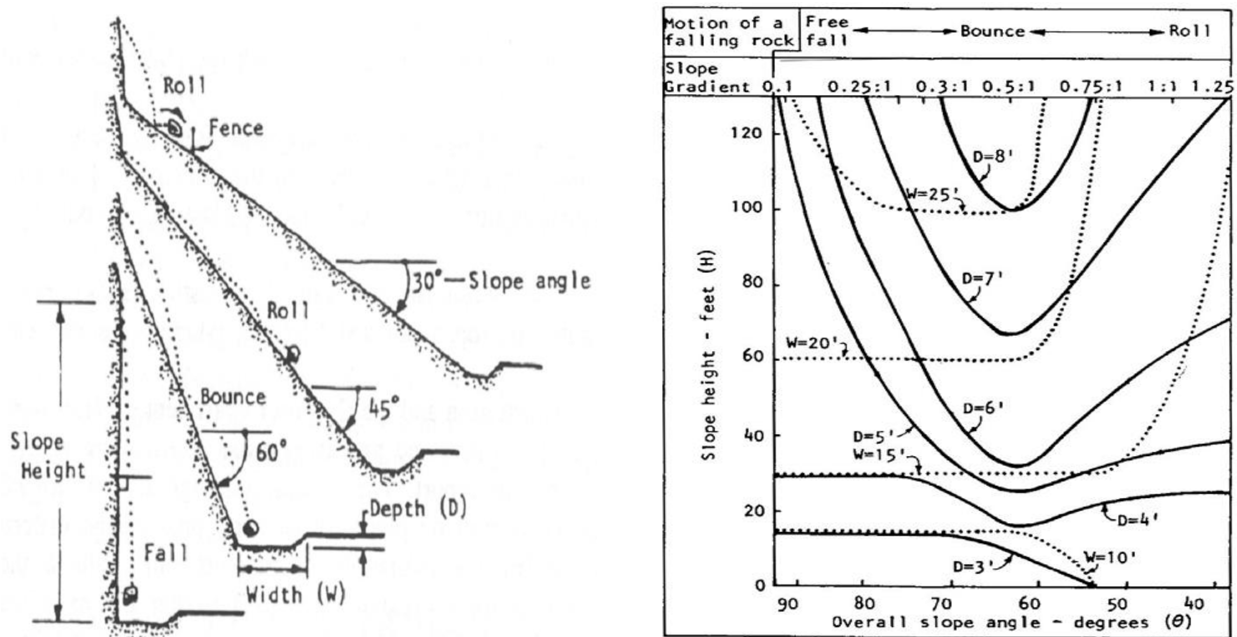
move, it descends the slope in different modes of motion such as Figure 1, which depends on the mean slope gradient. There are many different models for calculating runout zones of rockfall events such as empirical models, process-based models and GIS-based models (Geophysical Information System) (Dorren, 2003; Pierson et al., 2001). Empirical rockfall models (Tianchi, 1983; Keylock and Dommas, 1999) are generally based on relationships between topographical factors and the length of the runout zone of one or more rockfall events: correlation between the volume of the rockfall and the ratio of the maximum vertical drop to the maximum horizontal distance travelled and correlation between the volume of the rock and the area versed by the fallen mass. Rock falls can be a hazard for many facilities in mountainous terrain, particularly in areas with high rainfall and freezing temperatures, and seismic events occur (Wyllie, 2014). The randomness of the rock fall process has many sources. Stochastic model is capable for the simulation both the average behavior and the variability of the process. The reasonable stochastic approximations of the rock fall trajectories is obtained in all dimensions including runout, bounce heights and velocities (Preh et al. 2015).

Until now a large variety of empirical and process-based rockfall models exist provide the rockfall runout zones and predictions of runout zones where rockfall causes problems. For predicting rockfall runout zone then the integration of process-based models and a GIS-based are promising. In this paper, we have studied by theoretical and experimental to determine the parameters and influencing factors to simulate the orbit of fly rock and falling rocks. By empirical and simulation model of fly rock and rockfall, has made the risk of forecasting and proposed solutions to protected areas surrounding open pit mines.

Here, we will discuss the models rockfall simulation. These models rockfall simulations can be observed the geometric modeling of the boulder. A boulder is considered to be a point-mass (point like particle) or a rigid homogenous sphere with a certain radius (does not depend on the axis of rotation). A boulder may be a rectangular block with three parameters (height, width, depth) or be an arbitrary polyhedron. The boulders are its mass, the location of the center of mass within the body and the inertia tensor. Finally, the models rockfall simulation for rigid bodies with the contact interaction (rock and terrain: Signorini's law, Coulomb's law of dry friction). It is possible classified according to the modeling of the contact interaction: rebound



(a) (b)

Figure 1. Rockfall travel modes (a) and Ritchie's rockfall catch ditch design criteria (b).

impact models; non-smooth contact dynamics method

2. The non-smooth contact dynamics method appied to the rockfall

The NSCD method relies on a special formulation of the mathematical and mechanical background allowing us to deal with some extended kinds of laws. For the non-smooth in time, the occurrence of velocity jumps is a well know feature of the second order dynamics with unilateral constraints on the position even with continuous media.

The NSCD method is distinguishable from the smooth DEM (Cundall, 1980) due to the following features: an implicit schema for integrating the time discretized dynamical equation; a non-regularized interaction law (Signorini condition and contact law of Coulomb). LMGC90 declares the mechanical models of DFN and the contact behavior in the discontinuities. The code LMGC90 is a general purpose open-source software developed at LMGC Laboratory of Montpellier II, capable of modeling an extensive collection of deformable or under formable particles of various shapes, with different interaction laws. The models of fractured rock mass on Lmgc90 for the simulation and analysis under NSCD method. See in (Dubois and Jean 2006) and (Radjai and Richefeu 2009) for detailed explanation about the NSCD method (Nguyen 2016).

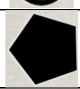
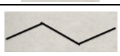
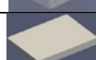
2.1. The rock geometry

The rock geometry is considered to be 2D/3D convex polyhedron and can therefore be defined as the convex hull of a finite point sets in the space. In these many choices: punctual contact with extended law (transmission of torque); multi-punctual contacts with classical interaction laws; continuous surfaced description; etc. Less trivial in usual cases: not strictly convex (cubes, bricks, etc.); only locally convex (general polyhedron, triangulated surface); not convex at all, it may be decomposed in not strictly convex shapes (Dubois 2012). Only in simplest cases (rigid body with strictly convex boundary) the interaction locus maybe considered as punctual.

2.2. Contact laws

Collision detection is a vast problem. The most popular approach is defining a contact force R = k*g at each contact point where *k* is a stiffness and g are a measure of the interpenetration between a pair of objects. The value *k* depends on the nature of the objects, the type of interaction, and other elements of the simulation. No matter how *k* is chosen. Hence, when *g* is negative which generate force. g is positive when the objects are no longer in contact.

Table 1. Geometry of 2D/3D convex polydedron of contactors.

2D shapes of contactors		3D shapes of contactors	
	disk, pneumatic disk		sphere
	hollow disk, pneumatic hollow disk		pill
	convex polygon		polydedron
	wall		point, point on the mesh surface
	point		patch on a mesh
	poly-line		plane
			cylinder, hollow cylinder

2.3. Signorini condition

The NSCD of objects in contact has been extensively studied in the mechanical simulation of a jointed rock mass in contact. A contradiction with Signorini's condition of contact (Figure 2a) which states that there exists a complementarity relation between the interpenetration distance g and the normal contact force R_N at the point of contact.

$$R_N \geq 0;\ g \geq 0;\ R_N * g = 0 \qquad (1)$$

Where g is the algebraic distance between two bodies at the point of contact and R_N is the amplitude of normal force needed to solve the contacts. In the case of frictional sliding, a tangential component R_T is introduced, leading to a contact force $R = (R_N, R_T)$. For the dynamical problem, it is more natural to formulate the unilateral contact in term of velocities with assuming $g(t_o) \geq 0$ then $\forall t > t_o$ if $g(t) \leq 0$ then $U_N \geq 0$, $R_N \geq 0$, $U_N * R_N = 0$ else $R_N = 0$.

2.4. Contact law of Coulomb

Following the contact law of Coulomb (Figure 2b), the sliding at the contact point only appears when the tangential component of the contact forces between two objects is larger than the sliding threshold. This condition is given as:

$$\begin{cases} g = 0 \ \rightarrow \ |R_T| \ \leq \ \mu\, R_N \ \rightarrow \text{nonsliding} \ \rightarrow \ U_T = 0 \\ U_T < 0 \ \rightarrow \ R_T = \ \mu\, R_N \ \rightarrow \text{sliding towards the back} \\ U_T > 0 \ \rightarrow \ R_T = \ -\mu\, R_N \ \rightarrow \text{sliding forwards} \end{cases} \qquad (2)$$

With $U = (U_N, U_T)$ is the sliding velocity vector between one object to another. $\mu = tan\ (\varphi)$ is friction coefficient and φ is the internal friction angle. It is existed a parameter $\rho > 0$ that $U_T = -\rho . R_T$ with frictional contact (Signorini-Coulomb).

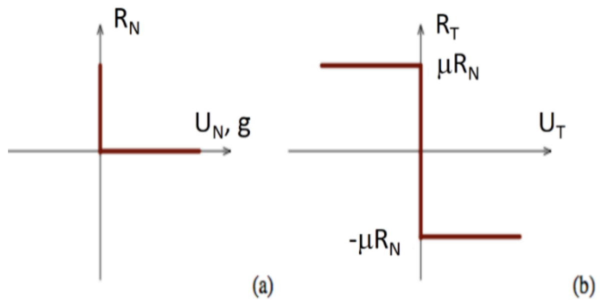


Figure 2. The relation curve of the contact in NSCD method: (a) Signorini condition and (b) Contact law of Coulomb.

2.5. Impact laws (Newton restitution)

Signorini unilateral and Coulomb dry friction are described and proposed the force laws for the non-impulsive contact force. The laws mean a non-regularized interaction law.

When shocks occur in a rigid body collection, the equation of motion and the interaction law are not sufficient to describe properly all the physics of the problem. There for the local phenomena as the inelastic behavior of materials at the interface; global phenomena as the wave propagation in the body bulk and should be taken into account long distance effects due to simultaneous impact.

In the case of binary shocks, three kinds of restitution can be used as law Newton restitution, Poisson restitution or Energy or Strong restitution. Newton restitution relates the velocity after ($U+$) to the velocity before ($U-$) impact. Poisson restitution, which relates restitution impulsion (Rr) to the compression impulsion (Rc) according to the decomposition of the shocks in a compression and restitution phase. Energy or Strong restitution, which relates restitution energy to compression energy.

With hard unilateral constraints, impulsive contact forces arise whenever contact closes with a negative relative velocity $U- < 0$. There is a jump in the generalized velocities U from the impulsive contact forces with that velocity in the normal direction is nonnegative $U_N \geq 0$. The velocity jump is called an impact law. We use the kinematic of coefficients of restitution (e_n) such as Newton restitution, is defined as:

$$Un+ = -\, e_n\, Un- \qquad (3)$$

The kinematic of coefficients of restitution was analysed to the normal and tangential components with respect to the plan surface, defining the normal (e_n) and the tangential (e_t) coefficients of restitution. Impact law for the normal component is well understood; it is not the case of the tangential component (for the rock terrain interaction as such elastic effects are absent). $e_n \in [0, 1]$ is the coefficient of restitution for the normal direction. The case with $e_n = 1$ corresponds to a reflection of the normal velocity whereas smaller 1 additionally dissipates energy.

The choice of the restitution coefficient is a difficult task for complex structures.

3. Rockfall simulations

An assessment of rockfall was undertaken to identify the potential fate of blocks that may detached from unstable pit lope faces and therefore, to improve the safety on the open pit mines. The simulation method proposed in this paper with 2D and 3D simulation model for rockfall based on the point-mass or the rigid homogenous sphere or the rectangular block or be an arbitrary polyhedron on the non-smooth contact dynamics method. The analysis was completed using Mathematica and NSCD method in LMGC90, program that simulates the trajectories of rocks falling from the slope (Nguyen et al. 2015a; Nguyen et al. 2015b).

The first in the environment Mathematica (Verdel 1997), a trajectory is modelled as a two dimensional rockfall simulation largely based on the slope geometry (point-mass 200kg, velocity along X 20 m/s, and velocity along Y -10 m/s). Using statistical analyses, method be calculated the probable trajectories, energy, velocity and bounce height envelopes for individual rock blocks. The slope cut can be modelled by the program, that the ultimate resting locations of rockfalls can be determined and the results graphed with comprehensive statistics calculated. The program requires input data such as the slope roughness, restitutions of normal and tangential rock energy, coefficient of rolling friction and rock mechanical parameters.

Table 2. Mathematica code of the rock fall trajectories.

```
Clear[duration];
duration[{{{xo_, _}, {vxo_, _}}, {{x1_, _}, {_, _}}}] := (x1 - xo) / vxo;

Clear[parab];
parab[{{{xo_, yo_}, {vxo_, vyo_}}, time_}, ts_:0.05, g_:-9.81] := Module[{t},
  Table[{t* vxo + xo, (g t^2)/2 + t* vyo + yo}, {t, 0, time, ts}]]

Clear[trajOne];
trajOne[ini : {{xo_, yo_}, {vxo_, vyo_}}, profil : {{_, _}..}, g_, damp_, anglealea_, spl_, timestep_] :=
  Module[{reb, gr, dates, para, trprof, xmin, ymin},
   reb = rebonds[ini, profil, g, damp, anglealea, spl];
   gr = Partition[reb, 2, 1];
   dates = Flatten[{Map[duration, gr], {0}}];
   gr = Transpose[{reb, dates}];
   para = Line[Flatten[Map[parab[#, timestep, g] &, gr], 1]]];

Clear[trajecto];
Options[trajecto] = {gravity → -9.81, damping :→ Random[Real, {0.3, 0.6}], anglerandom → 10 Degree,
   speedstop → 1, simulations → 10, timestep → 0.1};
trajecto[ini : {{xo_, yo_}, {vxo_, vyo_}}, profil : {{_, _}..}, opts___] :=
 Module[{g, damp, anglealea, spl, sim, reb, gr, dates, para, trprof, xmin, ymin, ts},
  g = gravity /. {opts} /. Options[trajecto];
  damp := damping /. {opts} /. Options[trajecto];
  anglealea = anglerandom /. {opts} /. Options[trajecto];
  spl = speedstop /. {opts} /. Options[trajecto];
  sim = simulations /. {opts} /. Options[trajecto];
  ts = timestep /. {opts} /. Options[trajecto];
  trprof = Transpose[profil];
  xmin = Min[trprof[[1]]];
  ymin = Min[trprof[[2]]];
  lines = Table[{Hue[Random[]], trajOne[ini, profil, g, damp, anglealea, spl, ts]}, {sim}];
  ListPlot[profil, Joined → True, Epilog → lines, AxesOrigin → {xmin - 10, ymin - 10}, PlotRange → All]]
```

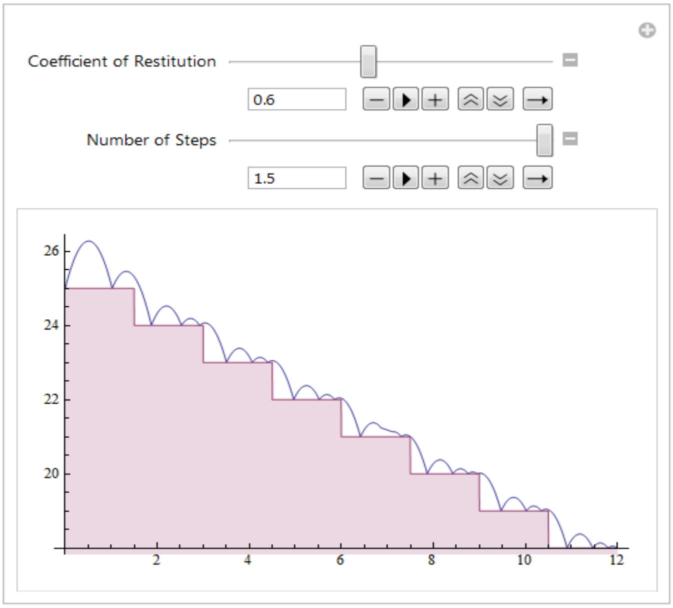


Figure 3. Results of the simulation of rockfalls trajectories from the top crest source area in Mathematica which shows the distributions of rockfall bounce heights above the ground level with the coefficient of restitution 0.6.

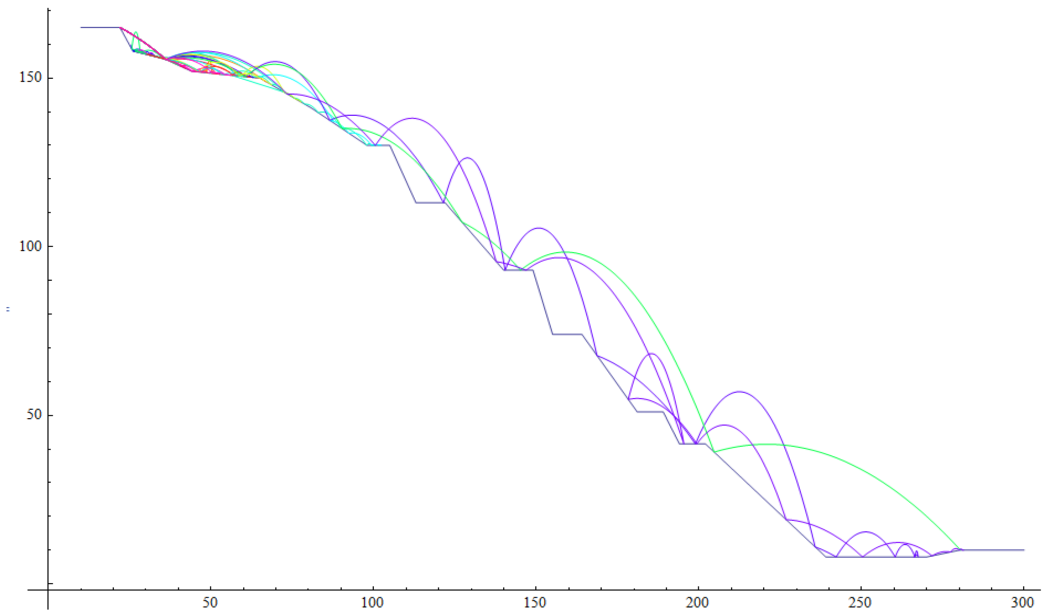


Figure 4. The trajectories in 2D models with stochastic approaches have been proposed to account for the variability of the rebound: $(trajecto[\{\{22,165\},\{20,-10\}\}, profilclues, speedstop \rightarrow 1, simulations \rightarrow 30, anglerandom \rightarrow 35Degree])$*; different colors lines are presented the rockfalls trajectories with stochastic approaches.*

Besides the uncertainty in the definition of the input parameters, stochastic variability is used Figure 3 and Figure 4. The model is given by the Mathematica code in Table 2.

Secondly, some models simulated the movement at the slope surface during rockfall with detailed characterizations for bouncing, sliding and rolling. In the code LMGC90 which is a general purpose open-source software, capable of modeling a large collection of deformable or undeformable particles of various shapes with various interaction laws. Models is used Coulomb's law of friction for calculating rolling and sliding velocities. We developed the models using both a tangential and normal coefficient for the efficiency of collision.

Boulder rockfalls usually generate faster movement as longer runout distances. A boulder was recorded to have fallen from the potential unstable slope blocks and travelled away from the toe of benches. It must be identified for the prevention of impacts on people and assets from rockfalls in open pit mines. These include flexible rockfall barriers, identifying effective berm widths, bunds constructed on production berms and using draped mesh. We can be observed horizontal locations for maximum trajectories of falling blocks are shown in Figure 5 (*a*).

4. Conclusion

Rockfalls are considered as a significant risk securities in open pit mines. Blocks falling from high up on benches can travel into the pit floor may destroy mining infrastructure as present a serious safety hazard for mine personnel. In the present paper, we have been used the simulation techniques of non-smooth contact dynamics with stochastic approaches and adapted for the efficient simulation of rockfall trajectories. The terrain geometry is constructed by the section 2D and 3D. The presented method allows for the 2D, 3D simulation of rockfall events on arbitrary slopes and with arbitrary rock geometries. The influence of shape on the rolling behavior of bodies can be studied with the presented simulation method in the environmental Mathematica and the code LMGC90. The models show that a barrier located at the pit floor and would be required to safely prevent the falling rocks reaching the mining operation zone.

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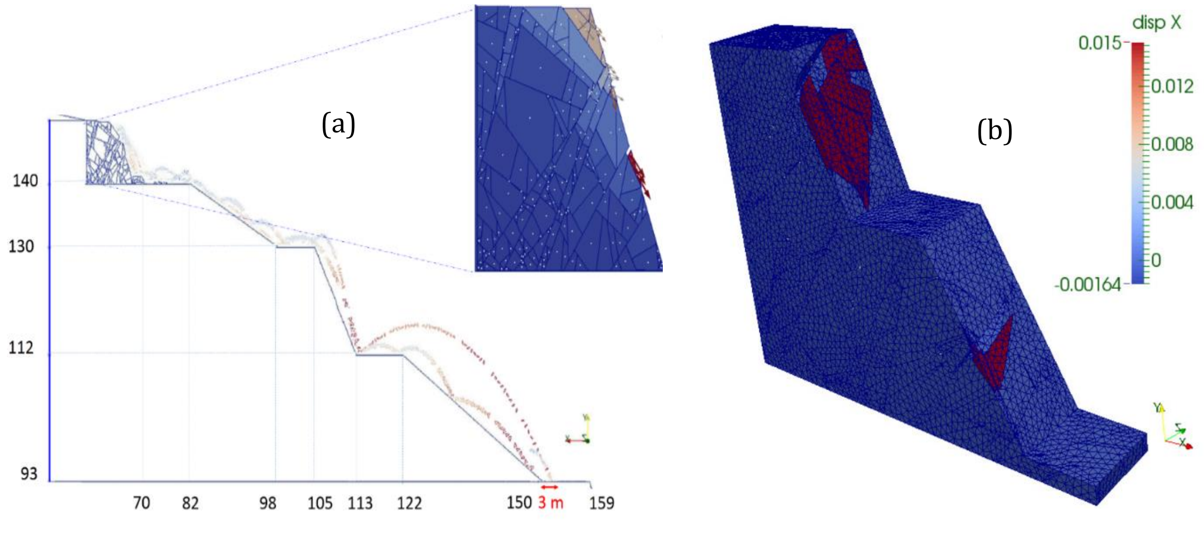

Figure 5. Simulated location of rockfall with stochastic approaches in the slope of Quarry Clues (France) (Nguyen et al. 2014) by LMGC90 in 2D (a) with a restitution shock law (RST_CLB, e_n=0.6), different colors lines are presented the rockfalls trajectories with stochastic approaches and in 3D is presented the location rockfall (b).

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