Modeling rockfall trajectories with non-smooth contact/impact mechanics

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ABSTRACT

Rockfall is an increasing problem in many mountainous regions throughout the world. In Switzerland during the summer of 2015 we observed escalating rockfall activity due to exceptionally warm temperatures and degradation of permafrost. Consistent and reproducible calculation methods are urgently required to predict rockfall inundation areas for hazard mapping and mitigation measure planning. In this paper we examine the use of non-smooth contact/impact mechanics to model the trajectory of falling rocks. Non-smooth mechanics parameterize the mechanical resistance of ground with consistent frictional parameters. These parameters account for rock shape and different rock propagation modes such as rolling, skipping, jumping and sliding; enabling a the characterization of different ground types, varying from extra soft to extra hard. We apply the new method to back-calculate a well-documented rockfall event demonstrating the important role of ground parameterization and rock shape in rockfall intensity mapping.

KEYWORDS

rockfall dynamics; modeling; hazard assessment

INTRODUCTION

The preparation of rockfall hazard maps and the planning of mitigation measures require reliable and consistent methods to predict rockfall runout, velocities and energies (Dorren, 2003; Volkwein et al., 2011). To date, rockfall modeling is based primarily on empirical shadow angle type methods (Glover, 2014) or lumped-mass/rigid-body type approaches (Schweizer, 2015). Discrete element methods that model the rock impact-rebound process using elastic-inelastic contact stiffness have also been applied to the rockfall problem (An and Tannant, 2007; Thoeni et al., 2014). These methods have been calibrated to a significant degree such that they can be applied to solve many practical problems.

But a significant problem with existing rigid-body rockfall models is that the rock-ground interaction is based on simple rebound physics. Coefficients of restitution are used to define the relationship between the incoming rock velocity and the post-impact velocity vector. The restitution coefficients therefore define the jump direction, height and length. This information is used directly in the preparation of hazard maps.

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The implicit assumption of rebound physics, however, is that rocks jump, a-priori. The entire rock-ground interaction is condensed to a single time point. Rocks do not slide or roll and remain in contact with the ground. Some rigid-body models account for rock rotations in the in-flight phase, but the influence of rock rotations during impact is generally ignored as the restitution coefficients are defined with respect to the translational velocity. The restitution coefficients are independent of the impact configuration, which depends on the rock shape and rock orientation at the time of impact (Glover, 2015).

To overcome this problem, many rockfall models use stochastic methods to describe the rock-ground interaction. Random number generators that account for the variability of the impact process essentially produce restitution coefficients. It is argued that the ground is variable and therefore the restitution coefficients must likewise vary. The variability of the impact configuration (rock size, shape, orientation, rotation) is not considered. Because rocks roll and slide before stopping (Fig. 1), many rigid-body approaches must also adopt ad-hoc stopping procedures to reproduce the observed runout distance.

The use of simple rebound physics coupled with ad-hoc stopping procedures limits the practical relevance and use of rockfall models. For example, important information from field observations (rock size, shape, scar length, scar depth, jumping, sliding, rolling motion) cannot be used to define consistent rockfall model parameters. It is therefore difficult to transfer modeling results from one geomorphological setting to another.

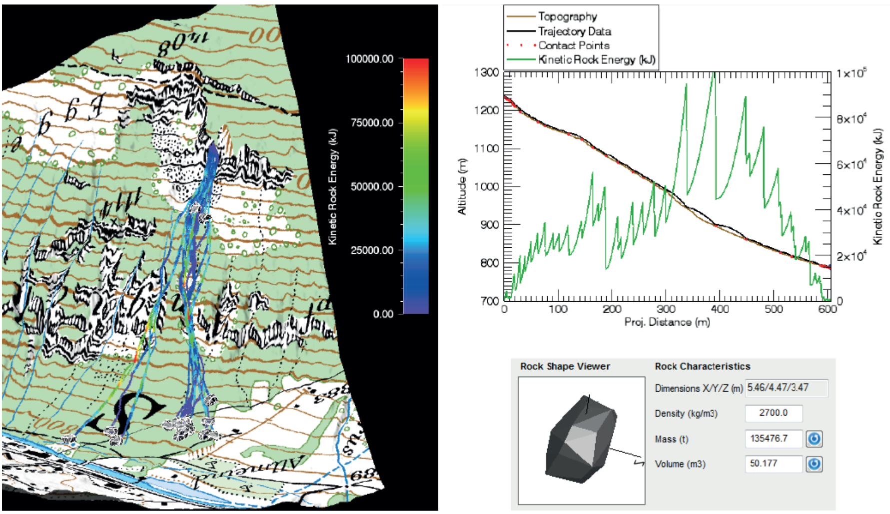


Figure 1: The rockfall model RAMMS::ROCKFALL applies non-smooth contact impact mechanics to the rockfall problem. Rock trajectories in three-dimensional terrain are calculated with variable rock shapes. Rock rotations and ground sliding are considered.

METHODS: NON-SMOOTH CONTACT/IMPACT MECHANICS

To overcome this problem, newly developed methods to treat the contact and impact were applied to the rockfall problem (Schweizer, 2015). The methods were introduced in the natural hazard program RAMMS (Christen et al. 2012) and applied to model observed rockfall events. The components of the model are:

– **Rock shape, size and impact configuration.** Rocks are described by point clouds that represent the complex surface topology (Fig. 2). Rocks can therefore have different forms, varying from equant to plate like. Rock size can vary from 0.5 m^3 (rockfall) up to 100 m^3 (blockfall). Impact forces are applied on the rock surface, depending on the impact configuration, leading to rock rotations and a natural modeling of lateral dispersion.
– **Rock rotations, quaternions and gyroscopic forces.** Rock rotations are considered not only in the in-flight phase, but also during the contact/impact phase. Thus, rolling and sliding can be modeled. Computationally efficient quaternion algebra is used to define the orientation of the rock. Gyroscopic forces resulting from the rock rotations will upright plate-like rock shapes producing dangerous wheel-type trajectories.
– **Set-valued contact laws with friction.** Set-valued force laws are used to describe stick-slip type phenomena (Fig. 2). They allow sliding with friction. These laws are essential to initiate rock-jumping and therefore long rock runout. Set-valued force laws are non-stochastic and therefore can be transferred to similar terrain. Restitution coefficients are not used to parameterize the rock-ground interaction, rather the sliding friction parameters. Soft ground allows more sliding and therefore true rock stopping without ad-hoc conditions.

PARAMETERIZATION OF GROUND FRICTION

The most significant difference between rebound models and non-smooth contact/impact models is the parameterization of ground friction. Rebound models simulate ground hardness with apparent restitution coefficients that describe the bounciness of the terrain for a single impact and point. In non-smooth models, ground impact is considered over a finite sliding distance s , which we term the scarring length (Fig. 2). The scarring length s is defined when any point on the surface of the rock is in contact with the ground. Contact is not defined with respect to the rock's center-of-mass, rather with respect to the complex surface geometry of the rock. Contact forces, including friction, are therefore introduced at the surface of the rock and cause rock rotations. The magnitude of the rotation at exit (when the rock departs the scar) are therefore dependent on the orientation of the when it hits the ground. A restitution coefficient ε is applied at the rock surface to account for energy dissipation in the normal direction. The model uses $\varepsilon = 0$ (fully plastic) for all terrain types. Bounce heights are purely a function of the impact orientation and the friction in the tangential direction. Hard ground does not allow sliding and therefore produces bouncing modes of propagation. The ground scar is being created at the speed and given by

$$s = \begin{cases} \|v\| & \text{if contact} \\ -\beta s & \text{if no contact} \end{cases}$$ ***Equation 1***

where $\|v\|$ is the sliding speed of the rock and $\boldsymbol{\beta}$ is a parameter controlling ramping effects, created when ground material is being displaced during the scar formation. When the ground is soft $\boldsymbol{\beta}$ is small because the ground is softer and the rock remains in contact with the ground longer (Fig. 2). The scar parameter $\boldsymbol{\beta}$ serves to extend the time that ground friction, or any other drag process, operates on the rock. It is therefore a useful parameter to describe low-lying vegetation layers in forests.

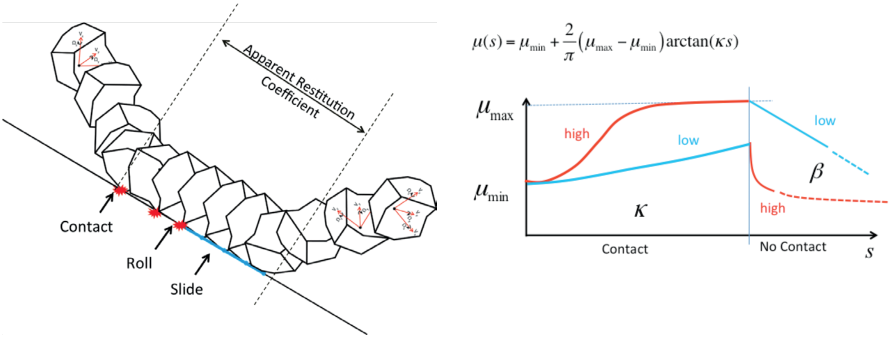


Figure 2: a) The interaction of the rock with the ground interface involves prolonged frictional sliding. This complex process is not governed by apparent restitution coefficients, rather mechanical properties of the ground under large deformation and strain-rates. Impulsive rebound forces coupled with frictional torques induce rock rotations leading to skipping/spinning-type propagation modes. b) Coulomb friction is parameterized as a function of the sliding distance using four parameters: $\boldsymbol{\mu_{min}}$, $\boldsymbol{\mu_{max}}$, $\boldsymbol{\kappa}$ and $\boldsymbol{\beta}$. An additional velocity dependent drag $\boldsymbol{v}$ accounts for viscous strain-rate effects during ground penetration/deformation.

When the rock is in contact with the ground friction is described by a combination of Coulomb friction $\boldsymbol{S_N}$ and viscous friction $\boldsymbol{S_V}$. These forces act in the tangential direction; that is, in the direction opposite to the rock velocity. The Coulomb friction coefficient $\boldsymbol{\mu(s)}$ for $\boldsymbol{s > 0}$ is given by the transcendental function

$$\mu(s) = \mu_{\min} + \frac{2}{\pi}(\mu_{\max} - \mu_{\min})\arctan(\kappa s).$$ ***Equation 2***

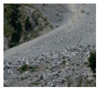
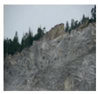
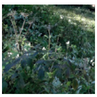
This function contains three parameters: $\boldsymbol{\mu_{min}}$, $\boldsymbol{\mu_{max}}$ and $\boldsymbol{\kappa}$, see Fig. 2. The parameter $\boldsymbol{\mu_{min}}$ defines the initial friction at the beginning of the ground interaction. Softer ground has lower $\boldsymbol{\mu_{min}}$ values. We then assume that during the ground interaction that the rock penetrates the ground and because of confining pressures ground material cannot be easily displaced out of the scar. This leads to an increase of friction, or scar hardening. The maximum friction is defined by $\boldsymbol{\mu_{max}}$ which we regard as a limit friction value, constant for all soils, but very low for easily deformable and porous ground materials like snow. An important parameter is $\boldsymbol{\kappa}$ which defines how a quickly the ground material changes from $\boldsymbol{\mu_{min}}$ to $\boldsymbol{\mu_{max}}$ which is a function of how easily a ground material compresses (in the sliding direction) during ground penetration.

These parameters may well be seasonally dependent, for example, a function of whether the ground is frozen or unfrozen, or a function of the water content.
The Coulomb friction term is supplemented with a viscous, rate-dependent friction

$$S_V = -\nu M \|v\| \quad \textit{Equation 3}$$

where ***M*** is the total mass of the rock and ***ν*** is the viscous drag coefficient. The softer the ground, the larger is the viscous coefficient.With this five parameter frictional model it is

Table 1: Ground categories and associated friction parameters in the RAMMS::ROCKFALL program

Category	**Picture**	**Description**	**Parameters**	**Category**	**Picture**	**Description**	**Parameters**
Extra Soft *Moor*		Very wet ground. Cannot cross without deep sink-in.	μ_{min}: 0.2 μ_{max}: 2 β: 50 κ: 1 ν: 0.9	Medium Hard *Shallow Meadow*		Rocks jump. Penetration depths are small. Ground is flat. Rocky debris is present. Non-paved mountain roads.	μ_{min}: 0.4 μ_{max}: 2 β: 175 κ: 2.5 ν: 0.5
Soft *Moist, deep Meadow*		Soft ground with many deep soil layers. Ground contains no large rock fragments. Often very moist. Foot indundations remain and are visible.	μ_{min}: 0.25 μ_{max}: 2 β: 100 κ: 1.25 ν: 0.8	Hard *Rock scree*		Rocks jump over ground. Mixture of large and small rocks. Usually without vegetation.	μ_{min}: 0.55 μ_{max}: 2 β: 185 κ: 3 ν: 0.4
Medium Soft *Deep Meadow*		Rocks penetrate meadow surface leaving impact scars. Soil is deep, few rock fragments.	μ_{min}: 0.3 μ_{max}: 2 β: 125 κ: 1.5 ν: 0.7	Extra Hard *Rockface / Bedrock*		Ground is very hard and is marginally deformed by rocks. Rockface and paved roads.	μ_{min}: 0.8 μ_{max}: 2 β: 200 κ: 4 ν: 0.3
Medium *Meadow*		Meadow is deep, but contains rock fragments. The meadow can be covered with vegetation.	μ_{min}: 0.35 μ_{max}: 2 β: 150 κ: 2 ν: 0.6	Snow		Rocks slide on snow surface.	μ_{min}: 0.1 μ_{max}: 0.35 β: 150 κ: 2 ν: 0.7

possible to establish seven general ground categories: Extra Soft, Soft, Medium Soft, Medium, Medium Hard, Hard and Extra Hard, see Table 1. These categories differ in the degree of a) sliding friction, b) bounciness, c) ground contact time and d) viscous drag. Depending on the rock-ground impact configuration, different propagation modes can result, varying from extreme braking in soft terrain (Extra Soft) to extreme jumps on hard ground (Extra Hard). An eighth category, Snow, was especially introduced to account for extremely low friction sliding modes.
The parameter values were determined using a combination of labortory tests, experimental investigations in the field and application on documented case studies (Glover, 2014). Clearly, more work will be performed in this direction in the near future.
As shown in Fig. 3, the different ground categories result not only in different runout distances, but also propagation velocities and spreading behavior. In this example an ideal 30° slope was used to compare the different hardness categories. An equant shaped rock was used and started with different orientations. The large spread in trajectories, especially in hard terrain, is therefore obtained by changing the initial conditions and not by random rebound coefficients during the process modeling.

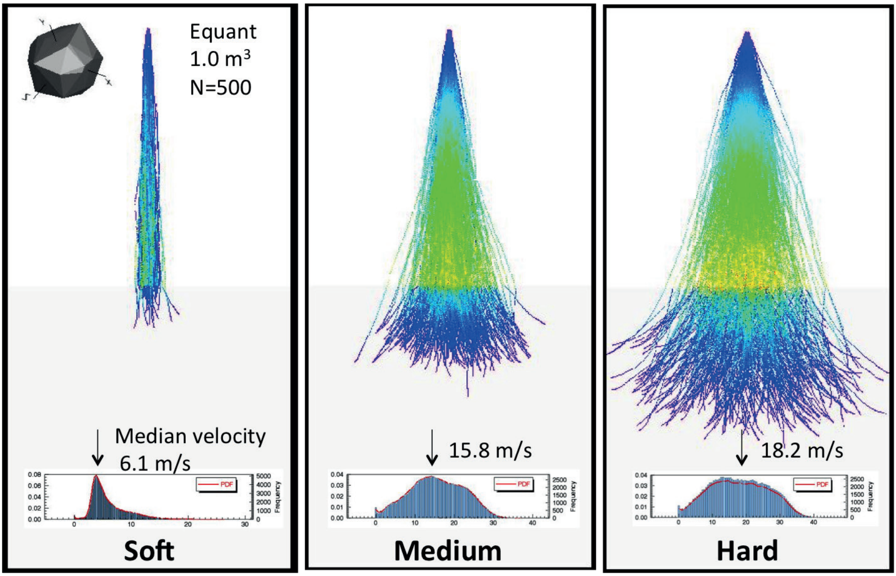


Figure 3: Simulation results using equant shaped rocks for three different ground categories: soft, medium and hard. Runout distances and calculated velocities. Note that spreading increasing with increasing hardness. The statistics are based on the maximum velocity in traversed cell.

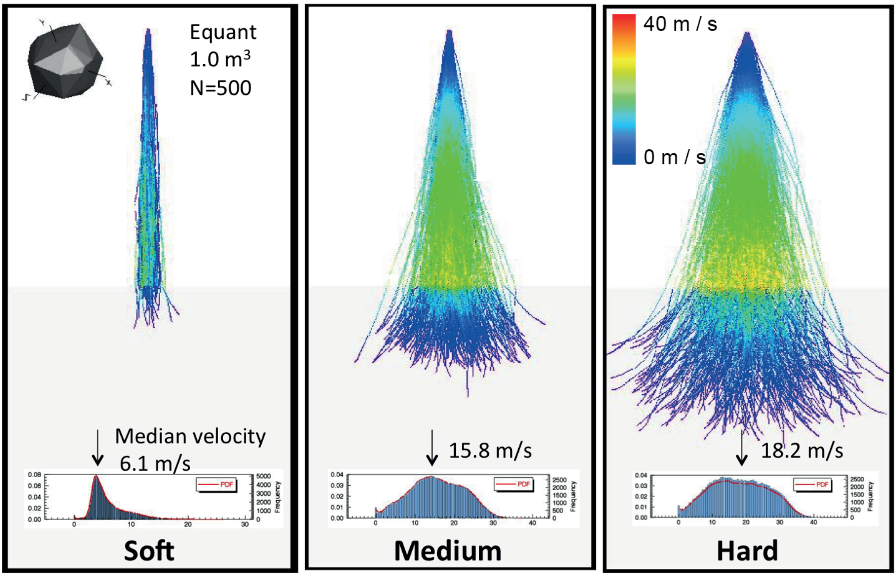


Figure 4: Disposition of the Brienz case study. On July 24, 2014 a large, plate-shaped limestone rock released and travelled to the road. Insets: the release zone, destroyed larch forest and toppled rock. The scar width indicated a wheel-like rolling propagation mode.

RESULTS: THE BRIENZ (GR) CASE STUDY

The village of Brienz, Canton Grisons (GR), Switzerland is the site of much on-going rockfall activity. On July 24, 2014 a 94 ton, 34 m³ plate-like rock detached from the upper limestone layer (1650 m a.s.l.) and descended down 800 m to the outskirts of the village (1150 m a. s.l.), barely stopping at the road connecting Davos and Lenzerheide (Fig. 4). The instable limestone layer is located above a deforming Schist stratum of Bündnerschiefer. The rock accelerated on the steep, transition zone covered with rock debris, possibly reaching peak velocities up to 50 m/s. The rock crashed into an old larch forest, knocking over several trees before decelerating and stopping on a flat meadow, located next to the road (Fig. 4).
Immediately after the event, a laser scanning of the visible portion of the rock was performed and ground scarring on the runout meadow documented. The width and length of the penetration scars indicated a skipping, rotating wheel-like propagation mode before the rock lost velocity and toppled to its final resting place (Fig. 4).
Simulations of the Brienz rockfall event using RAMMS::ROCKFALL were used to parameterize ground friction. The laser scanned rock was used to define the exact shape and dimensions of the rock (Fig. 5). In the simulations 500 rocks with different orientations were released from the point release zone identified in the field observations.

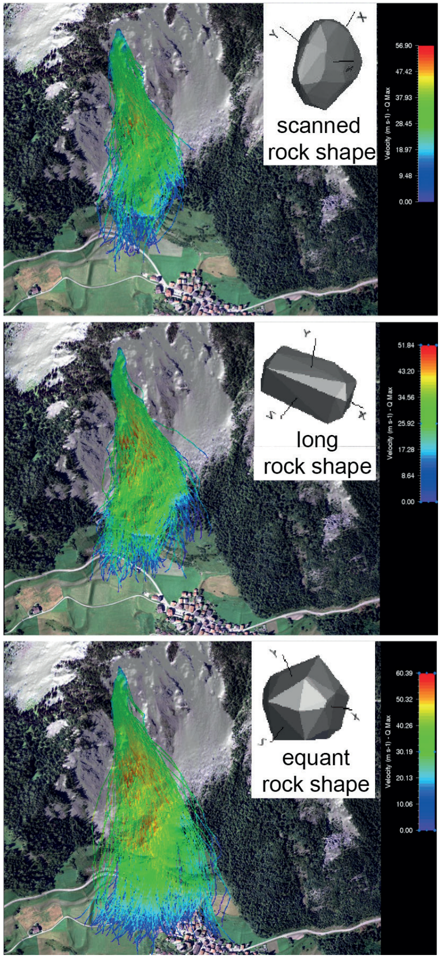


Figure 5: Role of rock shape on rockfall runout. Equant shaped rocks have, in general, the farthest runout distances. However, the real plate-shaped rock can also propagate large distances when it attains "wheel-rolling" modes.

The simulations revealed that long runout was only possible only if the rock managed to become upright and rotate around the wheel axis. For the terrain parameterization, category Hard was used in the release zone (limestone and schist stratums), Medium Hard in the transition zone (rock debris) and Medium Soft in the runout zone (Meadow). With this ground parameterization it was possible to model the observed runout, as well as the skipping propagation mode before the rock stopped. As in reality the simulated rock loses rotational stability at the end, wobbles and then topples on it side. Although the rock reached peak velocities of 50 m/s in the transition, mean velocities were considerably lower, approximately 30 m/s. Rotational velocities in the runout zone are only 4 rad/s (approximately half a rotation per second).

To demonstrate the importance of rock shape, elongated and equant rock shapes were tested with the same ground parameterization (Fig. 5). Elongated rocks had similar runout distances, but exhibited larger lateral spreading. Similar to the real (platy) form, many rocks stopped shortly after transgressing the transition zone. This was not the case for the equant shaped rocks: almost all rocks reached the runout zone and travelled slightly farther than both the platy and elongated forms.

CONCLUSIONS

Rockfall dynamics has traditionally relied on restitution coefficients to model rock-ground interactions. In contrast, non-smooth contact/impact models invoke friction laws to describe rock penetration and sliding. The frictional forces are applied on the surface of the rock, allowing the inclusion of rockshape into rockfall analysis. The main consequences of this new mechanical description are:

Firstly, and most importantly, non-smooth models simulate the complexity of the impact configuration that lead to the multitude of different rock propagation modes that govern rockfall: skipping, sliding, jumping and rolling. Rotational speeds and jump heights can increase or decrease, depending on the impact configuration, a fact supported by numerous observations (Glover, 2014). Modeling this behavior is required to determine the onset of stopping, which in stochastic rebound models is based on ad-hoc and user-defined cutoff criteria to bring to a halt the unlimited process of elastic rock bouncing.

The second consequence of non-smooth contact/impact mechanics is the possibility to model the mechanical properties of ground with consistent parameters associated with physical processes such as (1) material strength (μ_{min},μ_{max}), (2) material hardening leading to ramping and rock ejection (κ), (3) viscous, strain-rate dependent material behavior (ν) and (4) material weakening/softening at release (β). With these parameters it is possible to characterize different ground types, varying from extra soft (highly dissipative ground that can stop all rock shapes) to extra hard (where only rocks of non-equant shapes can be stopped realistically). Non-smooth contact/impact mechanics offers the possibility of modeling tree and stump impact with new physical models.

These two features of non-smooth contact/impact mechanics facilitate a realistic modeling of the variance of rockfall. It is necessary to understand this variance in order to develop better and more consistent methods of risk based hazard mapping.

The hard contact approach is more computationally demanding that simple rebound methods. The calculation of a single trajectory requires approximately 1 second on a standard desk-top computer. However, the computation time can increase when rocks slide and remain in contact with the ground. In our applications we are finding that the statistical distributions do not vary after several thousand rocks are used. In fact sometimes only

500 rocks are needed to obtain stable statistical values. For single slope domains the computational time is therefore not prohibitative; for large scale hazard mapping shadow angle methods will continue to provide the best computation times for large area analysis. The application of non-smooth contact/impact mechanics to the rockfall problem is now in its initial phase. Even at this stage, however, we believe the future impact on rockfall science, engineering and practice will be significant. One development that we are observing is an increased interest in rockfall experiments and examination of rockfall events in the field. Experimental measurements (e.g.to obtain rotational speed as a function of ground type) and field observations (e.g. documentation of scar lengths, rock shapes and jump lengths) can be used directly to calibrate non-smooth model parameters. Key is the modeling of rock jumping, rolling and sliding in three-dimensional terrain without introducing stochastic and non-physical rebound coefficients.

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