Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2019) 1612-1620

ECCOMAS
Proceedia

COMPDYN 2019
7th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Crete, Greece, 24–26 June 2019

NON-SMOOTH MECHANICS MODELLING OF ROCK-TREE AND ROCK-FOREST INTERACTIONS

G. Lu[1], A. Caviezel[1], M. Christen[1], A. Ringenbach[1], G. Meyrat[1], and P. Bartelt[1]

[1]WSL Institute for Snow and Avalanche Research SLF
Flüelastrasse 11, 7260 Davos Dorf, Switzerland
e-mail: guang.lu@slf.ch

Abstract. *Research on rockfalls and prevention of the associated damages is becoming increasingly important and active particularly due to the often climate-change- or earthquake-induced rock fragmentation in mountainous regions. Application of novel numerical methods on rock-tree/forest interactions simulation is an important part of the rockfall dynamics modelling, because understanding these issues would potentially improve the counter-measures management and hazards mitigation levels. Hence in this work the non-smooth mechanics coupled with hard contact laws is for the first time applied on modelling (non-)spherical rock-tree/forest impacts. The aim of this study is to probe and thus better understand from a fundamental level the role of rock shape in its energy dissipation during colliding with tree(s). The major findings are: (1) spherical and cubic rocks lose relatively more energy (in particular translational energy) than flat and long rocks within all impact regimes; (2) depending on the impact regime non-spherical rocks gain either stronger or weaker reflected rotation than a spherical rock; (3) rock rotational energy acts as an energy reservoir potentially influencing the impact-induced energy loss affected by rock shape and impact regime. Simulations of rockfalls along an ideally inclined virtual slope with forest cover demonstrate that rock shape dominates the entire energy dissipating process and consequently the run-out zone for these rocks.*

Keywords: Rockfall, Rock-Tree/Rock-Forest Interaction, Non-Smooth Mechanics, Modelling, Simulation.

Peer-review under responsibility of the organizing committee of COMPDYN 2019.
doi: 10.7712/120119.7022.19032

1 INTRODUCTION

Understanding the role of forest in rockfall hazards mitigation is significant in managing trees as barriers counter-acting landslide-induced damages to human lives and public infrastructures [1, 2, 3, 4]. To reach this goal numerical simulation researches have been extensively performed incorporating three aspects covering from rock to slope scales [5, 6, 7, 8, 9]. On a rock geometry level, most studies have concentrated on spherical rock shape aiming to reveal the rock-ground impact fundamentals by a very simplified modelling framework. However, recent experimental and numerical studies have already showcased that it is intrinsically difficult to reveal the rock energy dissipating process without considering the effect of rock geometry on a rockfall process [10, 11]. Turning to the rock-tree scale, two main topics have been addressed, i.e. the energy loss and the trajectory change of rocks after impacting with a single tree. These lead hopefully to a more clear picture of rock dynamics at the forest and slope scale, where the rock run-out zone and thus an effective forest management are key interests. Likewise, due to the currently spherical rock shape modelled in most investigations, an extention of the existing theories/findings to more general hazards situations is yet not available.

Hence this work intends to study and better understand non-spherical rock behaviour in particular its energy dissipation on a rock-tree impact level. The so-called non-smooth mechanics coupled with hard contact laws [12], due to its unique advantage in computational efficiency and simplification of mechanical representation [13], was for the first time applied on rock-tree interaction modelling, aiming to reveal how rock's energy, depending on its geometry, is dissipated during a tree stem colliding process. The originally implemented computational algorithms have enabled forest and slope scale simulations where the run-out zone of rocks being significantly influenced by their shapes was highlighted.

2 NUMERICAL SYSTEM SETUPS

In our rockfall problems rocks are modelled as three-dimensional, convex, polyhedral, rigid bodies, extracted from natural rock shapes using the software VisualSFM and Meshlab, with the object surface being discretized into about 100 points for an accurate rock-environment contact detection purpose. The governing equation for the non-smooth mechanics coupled with hard contact laws reads as $Mdu – h(q, u, t) = W(q)\lambda$ [12], where M is the mass term containing rock mass and moment of inertia, du is the change of rock's translational and rotational velocity in a given time step, $h(q, u, t)$ is the external forces acting on the rigid body such as the gravitational force, the damping force and the gyroscopic force, and $W(q)$ is the matrix recording the generalized force directions which transfer the contact force vector λ from the local contact points on the rock surface to the forces and torques at the rock center of mass. Note that λ may contain contact forces arising from both rock-tree and rock-ground collisions.

A tree stem is simplified as a non-deformable, truncated cone, with the symmetry axis pointing along the gravitational z direction. As shown in Fig. 1, this simplification captures the main feature of a general tree stem. The center R of the bottom surface specifies the x and y location on the terrain surface for a tree stem, the dimensions of which are given by the bottom circle diameter d_0, the top circle diameter d_1, and the height h. One also needs to appoint mechanical parameters for the rock-tree interaction calculation, i.e. the coefficients of restitution ϵ_N and ϵ_T in the contact normal and tangential directions respectively, and the coefficient of friction μ.

The critical issue one encounters when a virtual rock impacts with the tree stem is to identify when and where a contact occurs. The detailed mathematical derivation for the implemented rock-tree contact detection phase is out of the scope of this paper. For non-spherical rock and tree geometries this can be challenging while determining the set of contact points requires performing a series of mathematical calculations in time/spatial space. For instance, we have utilized the Axis Aligned Bounding Box (AABB) [14] method to pinpoint the cases when the rock is sufficiently close to a tree stem. Subsequently a tailored Separating Axis Test (SAT) [15] method has been employed to acquire the actual contact points between the rock and tree.

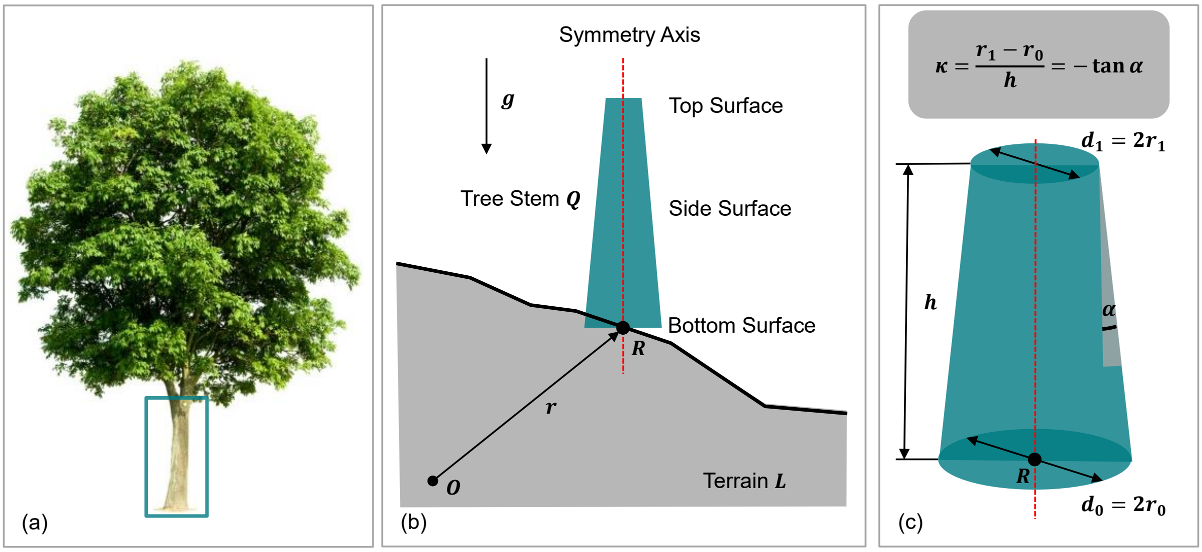


Figure 1: Scheme of the tree stem model: (a) A tree stem is geometrically modelled as a truncated cone. (b) The tree stem Q is placed on top of the terrain L with the symmetry axis aligning with the gravitational direction. (c) The parameter κ, which correlates the dimensions of a tree stem, is defined as $\kappa = (r_1 - r_0)/h$. Here κ is negative, i.e. the diameter of the tree's cross-section decreases from the bottom to the top.

Rock-Tree Impact			**Rock**
Parameter	**Min-Max**	**Test Values**	**Density**
d_0 (m)	0.05-0.6	0.55	2700 kg/m^3
μ (-)	0-1.2	0.6	**Volume**
ζ_{CT} (-)	0-1	random	0.02 m^3
v_{in} (m/s)	5-40	random	**Mass**
ω_{in} (rad/s)	0-60	random	54 kg
θ (°)	0-180	random	**Sphere Radius**
χ (°)	-40-40	random	0.168 m

Table 1: Typical ranges and actual values of the input parameters used in the rock-tree impact simulations.

Before setting up the numerical system (Fig. 2) some simplifications to the problem studied are made in order to highlight the effect of rock shape on its energy dissipation. First, geometrically the relative size between the simulated rocks and the tree stem is determined, i.e. we focus on rocks of a fixed volume 0.02 m^3 with the density being set at 2700 kg/m^3 (this leads to a rock mass $m = 54$ kg), and the tree diameters $d_0 = 0.55$ m and $d_1 = 0.45$ m. In addition, following the investigations by Toe et al. [8] and the truncated cone model used in this work, it is assumed that the rock-tree collision height does not govern the rock dynamics after impacts. Thus the height of the tree stem is chosen as $h = 10$ m, resulting in $\kappa = (r_1 - r_0)/h = -0.01$.

Furthermore, it is presumed that the tree stem can absorb any kinetic energy from the given small rock, i.e. the tree stem is a rigid body perfectly 'mounted' to the ground. Finally, the same as the rock-terrain interactions [12], the coefficients of restitution in the contact normal and tangential directions are both set to zero for rock-tree contacts, and the coefficient of friction on the tree stem surface is chosen as 0.6. Therefore, the remaining mechanical parameters that we must inspect are: the translational velocity v_{in} and the rotational velocity ω_{in} of rock at impact, the eccentricity ζ_{CT} defining the impact regime, and the impact angle θ and χ measured in the horizontal and vertical plane, respectively (Fig. 2b). The typical ranges (according to Toe et al. [8]) and the actual values of the input parameters used in the rock-tree impact simulations are listed in Tab. 1.

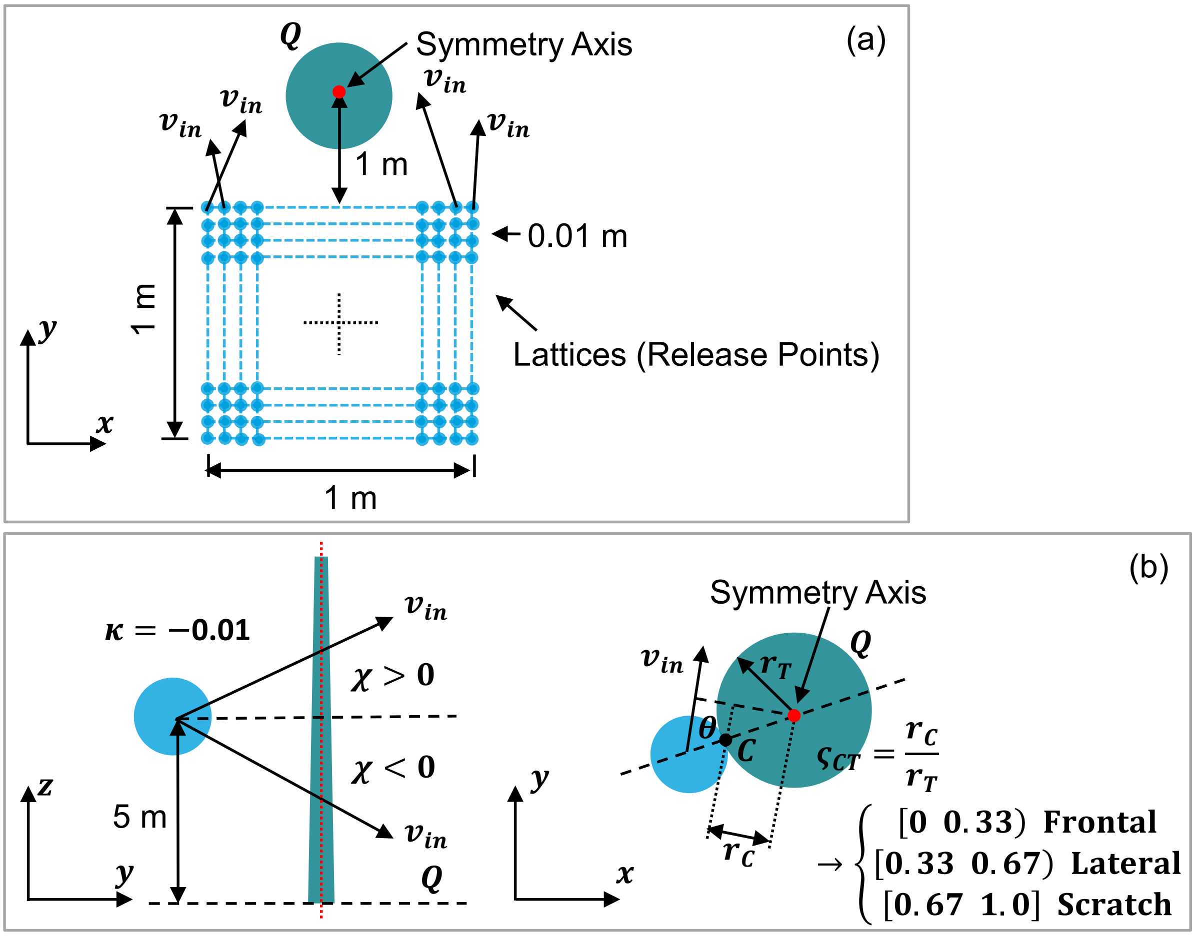


Figure 2: Definition of the input parameters for the rock-tree impact simulations: (a) the initial release conditions for rock (blue) impacting with a tree stem (green), shown in the xy plane, and (b) the two angles θ and χ and the eccentricity indicator ζ_{CT} which are used to describe the spatial impact position of a rock (blue) against a tree stem (green). According to the value of ζ_{CT} the impact regime can be distinguished into frontal, lateral and scratch [16].

To start the rock-tree impact simulation, rocks are released in front of the tree stem from the lattices spanning a 1 m^2 squared region (Fig. 2a). The distance between the neighboring release points in the x and y directions is 0.01 m. 10 identical rocks with varying orientations are released from each point, resulting in 11000 simulations in total for this rock shape. Initially, the rock is appointed with randomly translational and rotational velocities which fall into the parameter ranges suggested in Tab. 1. The initial rock release height is 5 m above the horizontal plane, and the mass center of rock has a minimum distance of 1 m away from the symmetry axis of the tree stem. From the simulated trajectories, only the rocks that have collided with the tree stem are collected, from which another 5000 trajectories are randomly sampled for analyses. This procedure guarantees that the number of effective simulations is invariant among different rock shapes investigated.

The following rock-tree/forest simulations are performed. Firstly as the control group the spherical rock (Tab. 1) is released against the single tree stem placed on the horizontal plane. Subsequently in the second group non-spherical rocks are simulated impacting against the same tree stem. We investigate one typically cubic, elongated and flattened rock each (Tab. 2). The volume of these natural rocks is scaled to 0.02 m^3. Here rock shape is quantified by the aspect ratio quantity $\Pi = l_{max}/l_{min}$, where l_{max} (l_{min}) is the length of maximum (minimum) principal axis of a rock. It is defined such that a rock is cubic only when $\Pi \leq 1.2$; otherwise the rock is either flat or long depending on whether l_{mid} is closer to l_{max} or l_{min}. Finally in the third group the non-spherical rocks modelled above are released from an ideal, virtual slope of inclination $\eta = 40°$ being covered with forest. The aim is to further identify if rock shape has a significant effect on falling rock's energy dissipation and, in turn, the run-out zone.

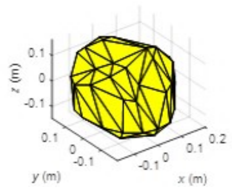
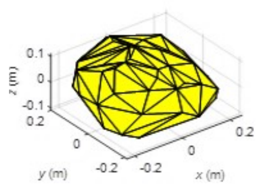
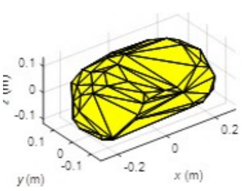
Rock Name	cubic1.2	flat2.2	long2.2
Dimension $x/y/z$ **(m)**	0.38/0.36/0.31	0.48/0.42/0.22	0.55/0.31/0.25
Aspect Ratio Π **(-)**	1.2	2.2	2.2
Rock Shape			

Table 2: Shape and dimensional parameters of the non-spherical rocks modelled in the simulations. All rocks are volume and mass equivalent to the sphere defined in Tab. 1.

3 RESULTS AND DISCUSSION

In this section results of our numerical simulations will be first presented on rock-tree impact level and then extended to rock-forest interaction scale.

3.1 Rock total/translational energy loss

The total and translational energy losses after rock impacting with the tree stem are first investigated since they are direct measures of how rock motion has been changed due to such a process. Note, non-spherical rocks may generate more than one impact to the tree stem owning to their rotational motion and shape. Nonetheless, in this work only the very first impact, i.e. the impact lasting from the beginning of contact to the first coming moment when there is no 'touching' between the rock and tree stem, is considered for the data analyses. The total energy loss is defined as $\Delta E_{total} = (E^-_{total} - E^+_{total})/E^-_{total}$, where E^-_{total} and E^+_{total} is the rock total energy before and after impact, respectively. Similarly, the translational energy loss is given by $\Delta E_{trans} = (E^-_{trans} - E^+_{trans})/E^-_{trans}$, where E^-_{trans} and E^+_{trans} is the rock translational energy before and after impact, respectively. Fig. 3 shows using probability density function

(PDF) plots the change of total energy investigated for different rock shapes within three impact regimes. It can be seen that, independent of rock shape, the highest probability for a total energy loss approximately decreases from 85% for frontal impact, to 70% for lateral impact, and then to 50% for scratch impact. This aligns with our common recognition that frontal impact tends to directly 'stop' the rock motion. Importantly, ΔE_{total} is higher for sphere and cubic1.2 than for flat2.2 and long2.2 in all three impact regimes, showing the effect of rock shape on its energy dissipation possibly relating to the rotational motion of the object. Overall ΔE_{trans} shows very similar trends in the PDF diagrams to the ones observed for ΔE_{total} in Fig. 3.

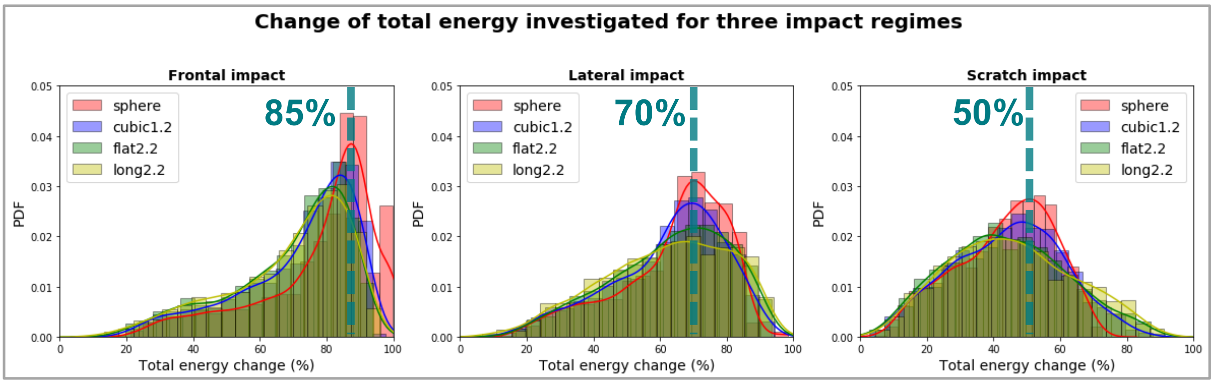


Figure 3: PDF plots for the change of rock total energy investigated for different rock shapes within three impact regimes. The total energy dissipation is higher for the spherical and cubic rocks than for the flat and long rocks.

3.2 Rock reflected rotation

It is worth further investigating how rock rotates, namely the reflected rotation, after impact, which adds another perspective to the change of rock motion. The change of resultant rotational speed is defined as $\Delta\omega = (\omega^- - \omega^+)/\omega^-$, where ω^- and ω^+ is the rock resultant rotational speed before and after impact, respectively. From Fig. 4 one clearly identifies that rocks gain different reflected rotations within different impact regimes. The change of resultant rotational speed is strongly linked to rock shape as well, i.e. after impact flat2.2 and long2.2 acquire stronger rotations for frontal impact but weaker rotations for scratch impact compared to sphere and cubic1.2. This observation can be in depths studied considering the rock's tensor of moment of inertia and the relative positions of contact points to the rock center of mass.

3.3 Rock energy partition after impact

To understand the rock rotational behaviour it is important to investigate rock energy partition after impact. This provides us more insights into the transfer of rock translational/rotational energy between each other. Fig. 5 plots rotational energy change, $\delta E_{rot} = (E^-_{rot} - E^+_{rot})$, as a function of translational energy change, $\delta E_{trans} = (E^-_{trans} - E^+_{trans})$, obtained for different rock shapes and impact regimes. In agreement with Fig. 4, for frontal impact rocks flat2.2 and long2.2 gain more rotational energy from their translational energy in comparison to rocks sphere and cubic1.2; whereas for scratch impact the trend is exactly the opposite. These observations point to the fact that rock rotational energy plays a role as an energy reservoir, which partially 'stores' rock translational energy during a tree impacting process. The 'functionality' of this energy reservoir apparently depends upon rock shape and impact regime. A further understanding requires dissecting the mass distribution and the contact position for these rocks.

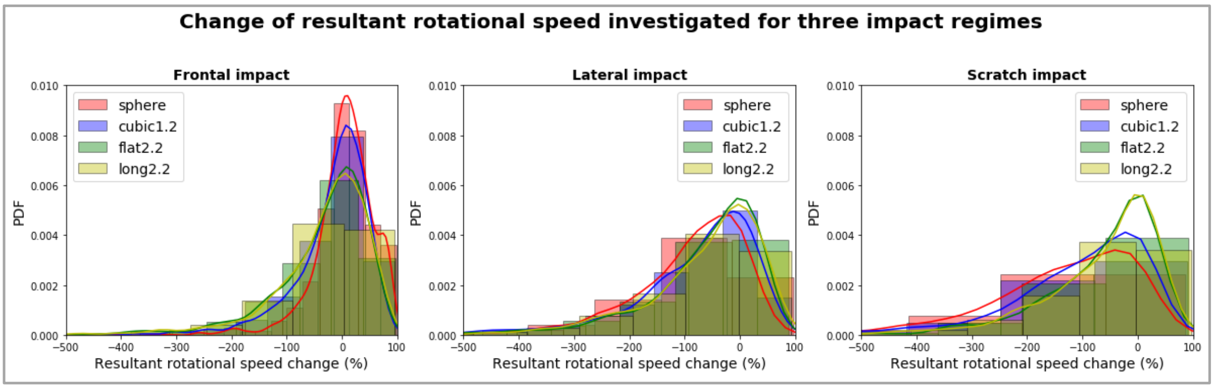


Figure 4: PDF plots for the change of resultant rotational speed investigated for different rock shapes within three impact regimes. Both rock shape and impact regime influence the rock reflected rotation.

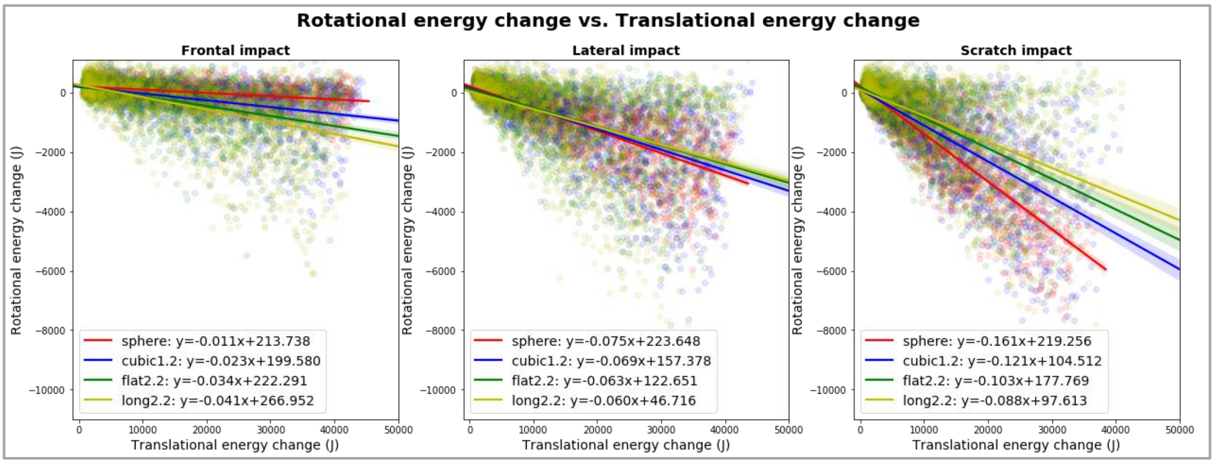


Figure 5: Plots of rotational energy change as a function of translational energy change investigated for different rock shapes within three impact regimes. Both rock shape and impact regime influence the rock energy partition.

3.4 Rock run-out zone formed on a slope

As final tests for rock shape effect on rockfall dynamics simulations are performed using the same group of non-spherical rocks on an ideal, virtual slope of inclination $\eta = 40°$. The aim is to investigate whether rock shape will significantly affect the run-out zone at the slope scale. Rocks, which are released at an altitude of 200 m corresponding to a slope length of 240 m, run through a forest and eventually land on the horizontal plane at sea level. In addition, trees are randomly distributed on the inclined terrain surface with a growth density 500 /ha. The mean diameter at breast height (DBH) for trees is 0.5 m with a standard deviation 0.05 m, and the averaged tree height is 22.87 m with a standard deviation 1.82 m. The coefficient of friction on the surface of tree stems is fixed to 0.1. For each rock shape in total 500 simulations are carried out with varying rock orientations before the release. Fig. 6 shows trajectory plots coloured by total rock energy for the three rock shapes simulated. Evidently, flat2.2 generates the longest run-out distance and the widest influencing region; while long2.2 corresponds to the opposite situation where the trajectory dispersion from the 500 simulations is the smallest. These observations confirm our assumption that rock shape is an important factor to be considered in rockfall run-out zone estimation. Out of a forest management perspective, it is crucial for the next step to understand the role of rock shape in its trajectory change after impacting with trees.

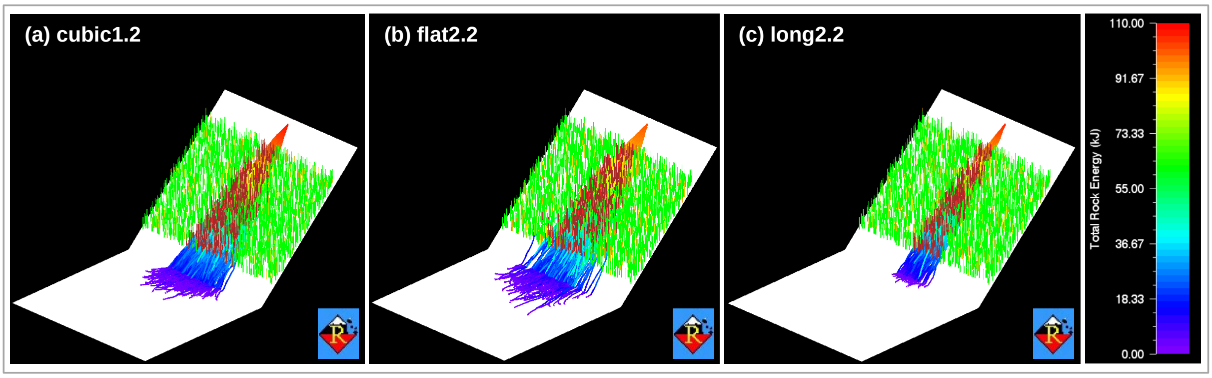


Figure 6: Influence of rock shape on rock run-out zone on an inclined, virtual slope with forest cover: plots of 500 (a) cubic1.2, (b) flat2.2, and (c) long2.2 trajectories coloured by rock total energy.

4 CONCLUSIONS

Non-spherical rock-tree interactions have been modelled within the non-smooth mechanics framework. Overall, simulations of rock-tree/forest impacts have exhibited interesting phenomena on both single tree and entire forest levels. Most importantly, it has been demonstrated that rock energy dissipation during the process of colliding with a tree stem is greatly influenced by rock geometry. The major findings are:

- Spherical and cubic rocks lose relatively more total energy (also translational energy) than flat and long rocks in all impact regimes.
- Depending on the impact regime non-spherical rocks can gain either stronger or weaker reflected rotation than spherical rock.
- Rotational energy acts as an energy reservoir potentially influencing the impact-induced energy loss dependent upon rock shape and impact regime.

Furthermore, the behaviour of non-spherical rocks reproduced by our non-smooth mechanics model in the entire forest slope simulations has well confirmed the significant role of rock shape in rockfall run-out zone development.

REFERENCES

[1] C. Moos, M. Fehlmann, D. Trappmann, M. Stoffel, L. Dorren, Integrating the mitigating effect of forests into quantitative rockfall risk analysis - Two case studies in Switzerland. *International Journal of Disaster Risk Reduction*, **32**, 55–74, 2018.

[2] S. Dupire, F. Bourrier, J.-M. Monnet, S. Bigot, L. Borgniet, F. Berger, T. Curt, Novel quantitative indicators to characterize the protective effect of mountain forests against rockfall. *Ecological Indicators*, **67**, 98–107, 2016.

[3] A. Radtke, D. Toe, F. Berger, S. Zerbe, F. Bourrier, Managing coppice forests for rockfall protection: lessons from modeling. *Annals of Forest Science*, **71**, 485–494, 2014.

[4] S. Dupire, F. Bourrier, J.-M. Monnet, S. Bigot, L. Borgniet, F. Berger, T. Curt, The protective effect of forests against rockfalls across the French Alps: Influence of forest diversity. *Forest Ecology and Management*, **382**, 269–279, 2016.

[5] J.-M. Monnet, F. Bourrier, S. Dupire, F. Berger, Suitability of airborne laser scanning for the assessment of forest protection effect against rockfall. *Landslides*, **14**, 299–310, 2017.

[6] D. Toe, F. Bourrier, L. Dorren, F. Berger, A novel DEM approach to simulate block propagation on forested slopes. *Rock Mechanics and Rock Engineering*, **51**, 811–825, 2018.

[7] C. Moos, L. Dorren, M. Stoffel, Quantifying the effect of forests on frequency and intensity of rockfalls. *Natural Hazards and Earth System Sciences*, **17**, 291–304, 2017.

[8] D. Toe, F. Bourrier, I. Olmedo, J.-M. Monnet, F. Berger, Analysis of the effect of trees on block propagation using a DEM model: implication for rockfall modelling. *Landslides*, **14**, 1603–1614, 2017.

[9] C. Corona, J. Lopez-Saez, A. Favillier, R. Mainieri, N. Eckert, D. Trappmann, M. Stoffel, F. Bourrier, F. Berger, Modeling rockfall frequency and bounce height from three-dimensional simulation process models and growth disturbances in submontane broadleaved trees. *Geomorphology*, **281**, 66–77, 2017.

[10] A. Caviezel, M. Schaffner, L. Cavigelli, P. Niklaus, Y. Bühler, P. Bartelt, M. Magno, L. Benini, Design and evaluation of a low-power sensor device for induced rockfall experiments. *IEEE Transactions on Instrumentation and Measurement*, **67**, 767–779, 2018.

[11] A. Caviezel, S. E. Demmel, A. Ringenbach, Y. Bühler, G. Lu, M. Christen, C. E. Dinneen, L. A. Eberhard, D. von Rickenbach, P. Bartelt, Reconstruction of four-dimensional rockfall trajectories using remote sensing and rock-based accelerometers and gyroscopes. *Earth Surface Dynamics*, **7**, 199–210, 2019.

[12] R. I. Leine, A. Schweizer, M. Christen, J. Glover, P. Bartelt, W. Gerber, Simulation of rockfall trajectories with consideration of rock shape. *Multibody System Dynamics*, **32**, 241–271, 2014.

[13] G. Lu, A. Caviezel, M. Christen, Y. Bühler, P. Bartelt, Modelling rockfall dynamics using (convex) non-smooth mechanics. *Numerical Methods in Geotechnical Engineering IX, Volume 2: Proceedings of 9th European Conference on Numerical Methods in Geotechnical Engineering*, Porto, Portugal, June 25-27, 2018.

[14] G. Lu, J. R. Third, C. R. Müller, Critical assessment of two approaches for evaluating contacts between super-quadric shaped particles in DEM simulations. *Chemical Engineering Science*, **78**, 226–235, 2012.

[15] S. Gottschalk, M. C. Lin, D. Manocha, OBBTree: a hierarchical structure for rapid interference detection. *Proceedings of 23rd annual conference on computer graphics and interactive techniques*, New Orleans, USA, August 4, 1996.

[16] L. K. A. Dorren, F. Berger, Stem breakage of trees and energy dissipation during rockfall impacts. *Tree Physiology*, **26**, 63–71, 2005.