Real-size rockfall experiment: How different rockfall simulation impact models perform when confronted with reality?

François Noël, Emmanuel Wyser, Michel Jaboyedoff & Marc-Henri Derron
Risk-group, ISTE, Institute of Earth Sciences, Faculté des Géosciences et de l'Environnement – Université de Lausanne, Lausanne, Switzerland
Catherine Cloutier, Dominique Turmel & Jacques Locat
Département de géologie et de génie géologique – Université Laval, Québec, Québec, Canada

ABSTRACT
To manage rockfall hazards, it is important to correctly estimate the reach distances and velocities of rock blocks. When rockfalls are primarily composed of freefall and rolling-rebound phases, free-flight velocities and reach distances are mainly the result of energy transfers that occur at impacts against the ground. In that case, it is better to calibrate the simulation models based on impacts. For this, accessible and shareable empirical data with which models can be tested are needed. Since steep terrains are difficult to access, we developed a fast acquisition method that does not require measurement of impact positions using survey methods, precision GPS or trajectory tracking algorithms. A video of a rockfall is used to identify impact position and localize them visually on a high-resolution digital terrain model. The time interval between the impacts is then used to reconstruct the 3D trajectories with their velocities. The method was tested at the Riou Bourdoux site. Characteristics such as 3D terrain orientation, incident and restituted velocities, incident angle and 3D deviation from 103 impacts were extracted from rockfall videos. Different existing simulation models are compared to the real values using a developed numerical tool in which the models are embedded with the empirical values. Some parameters can be adjusted in the tool (eg. Rn, Rt, soiltype, the slope surface roughness, etc.), while seeing the effect on the simulated values in real-time. This should help finding the right set of parameters for a given study site, especially if more than one rockfall simulation program is used. Of course, the given study site should be similar to the one from which the empirical values comes from. So feel free to contact us if you have empirical values to share!

1 INTRODUCTION

There is a multitude of rockfall simulation softwares to evaluate the possible propagation of rocks during their falls. Almost all of them, at one stage or another, use restitution coefficients. However, empirical restitution coefficients evaluated in studies (eg. Chau et al. 2002, Asteriou et al. 2012, Wyllie 2014) do not represent the same parameters as the restitution coefficient used in simulation softwares. Indeed, the different models are based on a particular set of equations. Different equations mean that the physics behind the models are not the same, and thus, the coefficient does not represent the exact same thing. In short, an apparent tangential restitution coefficient (R_T) observed during an impact does not correspond to the same R_T coefficient used in a certain model.

The user is therefore forced to use its judgement to set the right parameters, which is very subjective. Moreover, the same parameter used with a model might not generate the same behavior with another model. Here, the models are the set of equations used to compute trajectories. With that amount of subjectivity, a wide range of results can be achieved, even with one model, like Berger & Dorren (2006) observed, so it could be hard to pick the correct one.

To further complicate the transition from one propagation model to another, a sliding phase is sometimes combined with the rolling-rebound phase. The criteria for moving from one phase to the other vary according to the model. For the same site for example, one can find comparable travel distances with two models, but one of which considers the phases in a realistic way, while the other overestimates one phase and underestimates the other. This second model is not going to behave correctly for other sites, even if it got good reach distances for the first site.

To circumvent this problem, and at the same time to better validate the models and their parameters, Valagussa et al. (2015) recommend not using the travel distances / stopping location to calibrate the parameters. Instead, they suggested to make sure the simulated velocities correspond to those observed from real rockfalls.

Few empirical data including particle velocities throughout their fall are available to calibrate simulations based on velocities. Such data, would allow to compare the simulations obtained with different models.

Dorren et al. (2006) surveyed the location of impacts points of rockfall field tests for the development of their rockfall simulation model Rockyfor3D (Dorren 2015). They then estimated some 2D particle velocities from video footage captured at 25 frames per second (fps) perpendicular to the trajectories. This approach requires a site that can be accessed on foot, and therefore not too exposed. In addition, surveying is time consuming; 8 trajectories could on average be acquired per day spent in the field. For this reasons, the methodology is often not practicable.

For their part, Asteriou and Tsiambaos (2016) recently managed to 3D track small-multicolored cubes of 0.03 m sides with an image recognition algorithm and stereo-photogrammetric processes in order to propose a new empirical model of impact. They filmed the cubes falling using two 720p HD cameras at 60 fps. They also adjusted the measured velocities based on ballistics equations. Such an approach, however, requires a strong contrast between the blocks and the background so that the algorithm can isolate the position of the particles. The shape of these must also be relatively regular (cubes & colored spheres in this case).

To circumvent some limitations of these methods, we propose a new rapid acquisition method that combines some of the features of the previous approaches with the use of high-resolution 3D point cloud terrain model. The method does not require measurement of impact positions using survey methods, precision GPS or trajectory tracking algorithms. It has been tested in a preliminary way at the Riou Bourdoux site. Then, the particle impact behavior from our first acquired empirical data is explored. Finally, many existing simulation models are compared to the impacts acquired with the proposed method.

2 ACQUISITION METHOD

Table 1. List of variables

t	Time	s
$\vec{X}$	Position of the particle in 3D space	m
$\vec{v}$	Translational velocity of the particle	m/s
$\overrightarrow{v_T}$	Tangential component of the velocity	m/s
$\overrightarrow{v_N}$	Normal component of the velocity	m/s
$\vec{\omega}$	Angular velocity	rad/s
$\vec{a}$	Acceleration of the particle	m/s^2
g	Gravitational acceleration (~9.81 m/s^2)	m/s^2
$\vec{N}$	Vector normal to the ground surface orientation	-
θ_1	Incident impact angle with the ground	°
θ_{dev}	Angular deviation that the particle undergoes by the impact	°
R	Total kinematic coefficient of restitution	-
R_N	Normal kinematic coefficient of restitution	-
R_T	Tangential kinematic coefficient of restitution	-

To acquire 3D impact characteristics from real-size rockfall experiment using the developed acquisition method, a high precision and noise free 3D model of the site is needed. SfM and TLS methods can be used alone or combined for this purpose.

The falling blocks have to be filmed at a resolution high enough and with a field of view that allows a precise visual recognition of the impacts with their position relative to the site. So, filming from more than one point of view is highly recommended.

The frame rate (fps) should be adapted according to the anticipated angular rotation speed of the particle to get at least about five frames per turn. A minimum of 30 fps is often needed, 60 fps and over are recommended.

Analyzing the timestamped video footage frame by frame while zooming in the 3D terrain model with a similar point of view, the precise impact locations and time of impact can be noted. It is not needed to track the blocks from their exact first impact or until their last ones. What is important is to have a series of precisely localized and timed impacts.

Using the following equations, the 3D partial trajectories can be reconstructed with their impact characteristics. This is an iterative process that can be program to simplify and accelerate its application.

Position during the balistic / free fall phase:

$$\overrightarrow{X_t} = \overrightarrow{X_{t0}} + \overrightarrow{v_{t0}}t + \frac{1}{2}\overrightarrow{a_t}t^2 \quad [1]$$

Translational velocity:

$$\overrightarrow{v_t} = \frac{d\overrightarrow{X_t}}{dt} = \overrightarrow{v_{t0}} + \overrightarrow{a_t}t \quad [2]$$

Acceleration:

$$\overrightarrow{a_t} = \frac{d\overrightarrow{v_t}}{dt} \quad [3]$$

Neglecting the drag due to air resistance, the acceleration components are:

$$\overrightarrow{a_t} = \begin{bmatrix} a_{xt} \\ a_{yt} \\ a_{zt} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} \quad [4]$$

Let's say that we have three successive impacts, respectively a, b and c. With the previous ballistic equations, the restituted translational velocity for the impact b is given by:

$$\overrightarrow{v_{b2}} = \begin{bmatrix} v_{xb2} \\ v_{yb2} \\ v_{zb2} \end{bmatrix} = \begin{bmatrix} \Delta X_{xbc}/\Delta t_{bc} \\ \Delta X_{ybc}/\Delta t_{bc} \\ \frac{\Delta X_{zbc}}{\Delta t_{bc}} + \frac{1}{2}g\Delta t_{bc} \end{bmatrix} \quad [5]$$

The incident translational velocity:

$$\overrightarrow{v_{b1}} = \begin{bmatrix} v_{xb1} \\ v_{yb1} \\ v_{zb1} \end{bmatrix} = \begin{bmatrix} \overrightarrow{v_{xa2}} \\ \overrightarrow{v_{ya2}} \\ \overrightarrow{v_{za2}} - g\Delta t_{ab} \end{bmatrix} \quad [6]$$

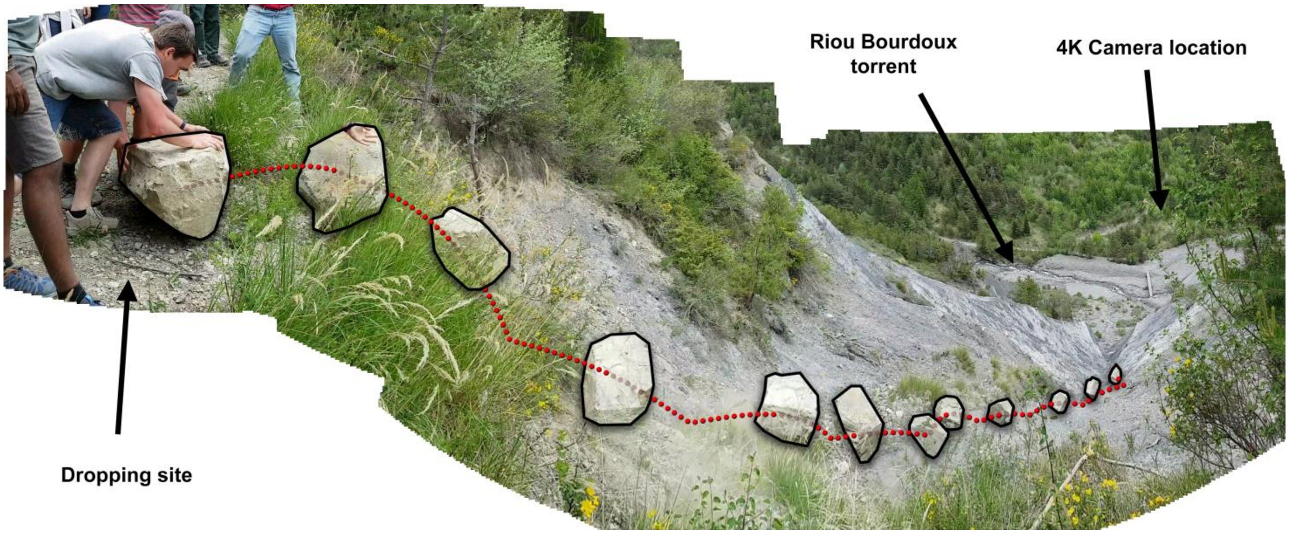

Figure 1. Terrain configuration for the drop tests. Here, multiple stitched frames are showing the position of the block that is contoured.

Then, knowing what are the incident and restituted velocities, apparent coefficients of restitution can be calculated for each impact. The normal apparent kinematic coefficient of restitution is given by:

$$R_N = \frac{\|\overrightarrow{v_{N2}}\|}{\|\overrightarrow{v_{N1}}\|} \quad [7]$$

Tangential apparent kinematic coefficient of restitution:

$$R_T = \frac{\|\overrightarrow{v_{T2}}\|}{\|\overrightarrow{v_{T1}}\|} \quad [8]$$

The geometric characteristic of the impact can also be analyzed. The incident impact angle is given by:

$$\theta_1 = 90 - \sin^{-1}\left(\frac{\|\overrightarrow{v_1} \times \vec{N}\|}{\|\overrightarrow{v_1}\|\|\vec{N}\|}\right) \quad [9]$$

The angular deviation:

$$\theta_{dev} = \cos^{-1}\left(\frac{\|\overrightarrow{v_1} \cdot \overrightarrow{v_2}\|}{\|\overrightarrow{v_1}\|\|\overrightarrow{v_2}\|}\right) \quad [10]$$

Finally, when both the visually identified impact locations and their 3D reconstructed trajectories match with those from the video footage, the 3D impact characteristics can be saved… And ideally shared with the rockfall analysis community!

This acquisition method allows reconstruction of part of the rockfall trajectories in the rolling-rebound and free falling phases. It does not allow for the reconstruction of trajectories where the blockis in constant contact with the ground, such as during the sliding. Experimental rockfalls can follow one another, only a small delay is necessary to let the dust fall. Steep exposed slopes can be studied, because all the measures are remotely taken.

This methodology can be extrapolated to get timed location of the blocks propagating through on the other phases of movement and also to obtain stopping locations. Interpolation in between the picked points, using appropriate equations, would allow reconstructing these segments of the trajectories. In this technical paper, however, we focus only on the impact portion to compare models.

3 ON SITE ADAPTED METHOD

We quickly tested the method in Barcelonnette, France in June 2017. The tests consisted of throwing about 15 angular limestone blocks of about 30-40 cm of diameter downslope (Figure 1).

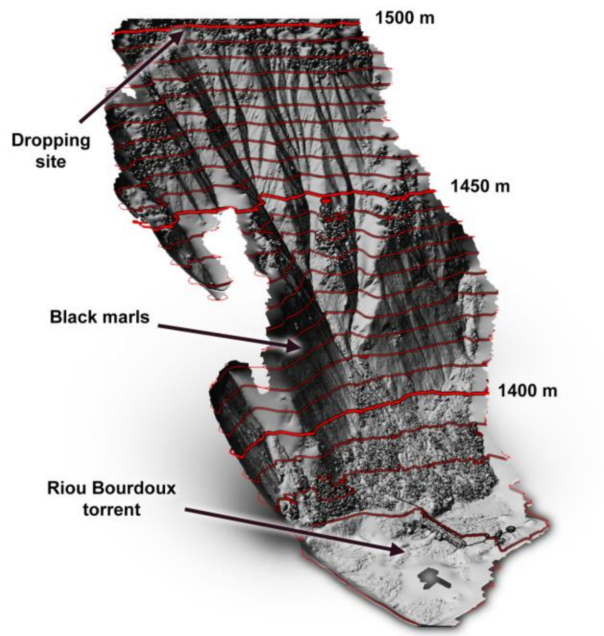

Figure 2. The 116 m high gully near the Riou Bourdoux torrent where the experiment was carried on.

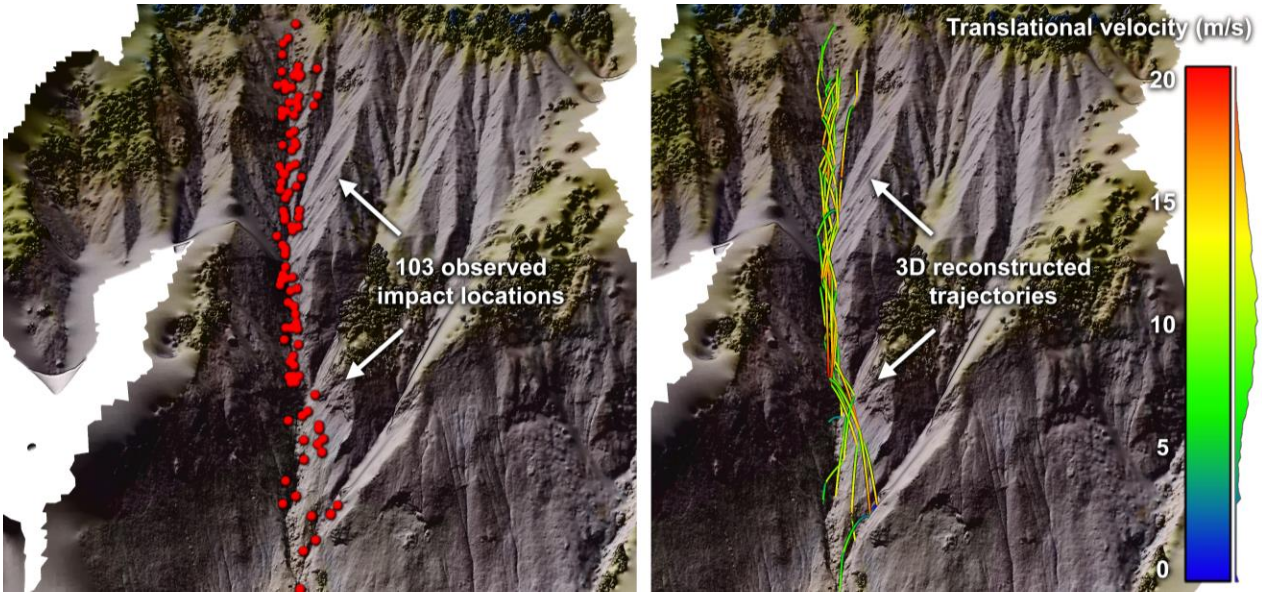

Figure 3. High resolution TLS meshed 3D point cloud of the Riou Bourdoux site where the method was tested with the 103 impacts. The scene is here shaded with computed hillshade and Eye Dome Lighting values based on the local terrain orientation. This helps prevent erroneous use of low resolution areas or artifacts that could be masked if the data were textured from high resolution photos.

During about half a day, a topographic model of a 116 m high gully near the Riou Bourdoux torrent was acquired with an Optech ILRIS LR terrestrial laser scanner (Figure 2), photos were taken as well to build an SfM model and rockfalls were filmed (Figure 1).

The gully is mainly composed of black marls. The upper part is quite steep, with inclinations of over 53°. The major part of the slope where impacts were noted is inclined at 40°. However, along the channel bed of the gully, the sides are steeper. The lower part at the exit of the gully forms a small colluvium at 16° where most of the blocks stopped.

For this first experiment, rockfalls were filmed with a handheld stabilized 4K camera at 30 fps from only one point of view near the bottom, on the other side of the Riou Bourdoux torrent (Figure 1). This is far from ideal, because having only one point of view in certain condition made the precise identification of the impact point harder. But because only one timed impact location can reproduce the same parabola than one observed, it was possible to fine-tune the picked location by iteratively constructing the 3D trajectory, and validating its shape with the video footage. Even with an automated 3D trajectory reconstruction from the measured timed locations, this was very time expensive, so it is really recommended to use more than one point of view, especially considering the value to money of cameras and drones we can get these days!

Finally, 103 impact locations were identified from this experiment (Figure 3). The others were discarded, sometime because it was not possible to precisely identify their locations, or because the blocks shattered at impact. Coefficient of restitution of first and last impact of a trajectory segment cannot be obtained, because both incident and restituted velocities are needed.

4 EMPIRICAL DATA ANALYSIS

Many correlations can be explored from the acquired data, we will focus on: 1) the normal apparent kinematic coefficient of restitution R_N with the incident impact angle with the ground θ_1; 2) R_N with the normal impact velocity $\|\overrightarrow{v_{N1}}\|$; 3) the tangential restituted velocity $\|\overrightarrow{v_{T2}}\|$ with the tangential incident velocity $\|\overrightarrow{v_{T1}}\|$ and 4) the total apparent kinematic coefficient of restitution R with the 3D angular deviation θ_{dev} caused by the impact.

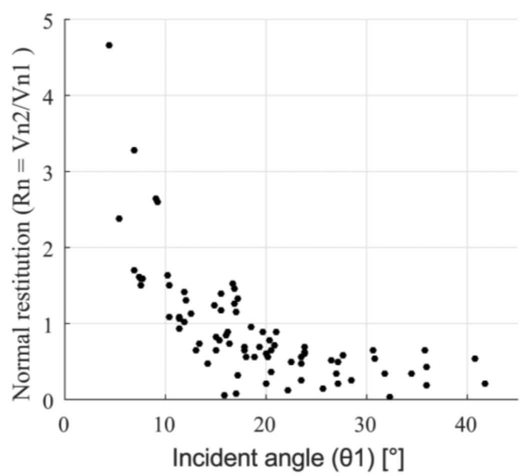

Figure 4. Normal apparent kinetic coefficient of restitution as a function of the incident impact angle with the ground.

First, on Figure 4, many R_N are above one, meaning that many impacts were restituted with a higher normal velocity than the velocity before the impact. This occurs when θ_1 is low (below 20°). This follows the same trend observed on natural terrains by Wyllie (2014) and Asteriou (2012). In our study, R_N values as high as 24.4 were observed, but the vertical axis of Figures 4 and 5 were limited to a value of 5 to better see the values in between zero and one. R_N - θ_1 - $\|\overrightarrow{v_{N1}}\|$ sets of values out of range of the graphs are: [24.4 - 0.3° - 0.1 m/s; 8.1 - 1.1° - 0.3 m/s; 5.1 - 4.3° - 0.8 m/s].

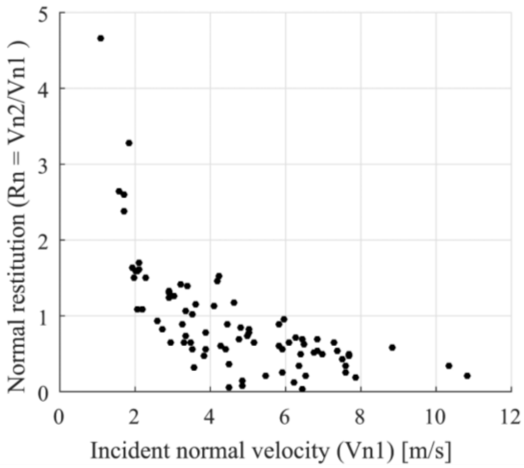

Figure 5. Normal apparent kinetic coefficient of restitution as a function of the incident normed normal velocity.

Secondly, Figure 5 shows the relationship between, R_N and the normalized normal incident velocity. A similar trend is observed, where the R_N value increase with lowering $\|\overrightarrow{v_{N1}}\|$. Values of R_N over one should not be misunderstood; there is no energy creation here but simply a transfer that could come from the rotation and/or the tangential velocities / kinetic energies. More investigations are needed to see how they correlate.

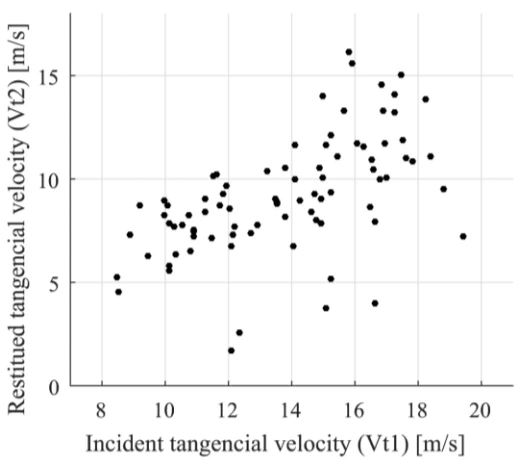

Figure 6. Restituted normed tangential velocity as a function of the incident normed tangential velocity.

Figure 6 shows the restituted normalized tangential velocities in relation with their incident ones. On this graph, the slope of a linear fit is R_T. The values are highly scattered, with some outliers, but a linear trend could be suggested, with a constant R_T of 0.66 with a R^2 of 0.31. This is similar to what was observed by Wyllie (2014).

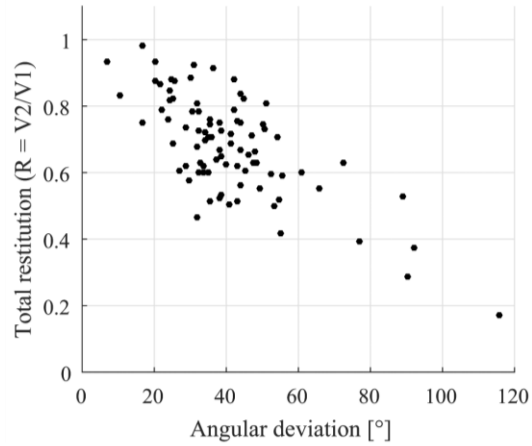

Figure 7. Total apparent kinetic coefficient of restitution as a function of the 3D angular deviation.

Figure 7 groups together the two main elements that control the propagation distance: the 3D deviation and the velocity change that occur during an impact. Such a graph is a very good tool to investigate the global trajectory or block propagation behavior. To put into perspective, a block that does not change trajectory, so without impact, would have a zero deviation. And one that would return from where it came from would have a maximum deviation of 180°. Here, a linear trend can be observed, where the amount of restituted velocity get lower with increasing deviation.

To explain what we observe, let’s imagine a rock traveling in space at a given speed. To induce a certain deviation in its course, a rocket propeller attached to it should provide some work at a certain angle against the rock. Back on Earth, the ground might give this work when an impact occurs. But because energy can’t be created, it has to come from somewhere. Some kinetic energy of the particle might be transferred to the ground at impact, and then given back through elastic deformation, inducing the observed deviation. However, the more energy is transferred, i.e. bigger deviation, the greater the "loss" by plastic and brittle deformation might be.

Some questions might fully or partly remain:

1) What controls the amount of energy transferred to the ground? Is it the incident impact angle alone, or combined with the particle rotation, the normal incident velocities/energies?

2) Does this behavior change given the encountered material (more plastic, more rigid, with different water content…); and by what amount?

3) To which extent the slope roughness and shape of the block affect the observed scattering?

4) How does the deformation of soft ground during impact affect the deviation?

5) Does these results are scalable to terrains with different geometries and with particles of different sizes and shapes?

5 ROCKFALL IMPACT MODELS COMPARISON

5.1 Model comparison methodology

Although some questions remain about the physics of the observed relationships, we compared different rockfall impact models with the observed empirical values. To do this, we embedded many rockfall impact models in our simulation software in development, named Trajecto3D. Instead of performing complete simulations on the 3D digital terrain using these models, the input conditions are imposed according to those of the measured impacts. The obtained results then focus on what happens on impact, and can therefore be analyzed objectively in the same way as the empirical values. In doing so, the analysis of velocities variations during free fall phases is also avoided. Indeed, it is useless to compare the free fall of the models since it is considered in the same way.

In this technical paper, six impacts models/equations whose documentation is transparent enough are compared and presented in alphabetical order: 1) one of the first models used with computer (Azimi & Desvarreux 1977); 2) Rockyfor3D v5.2 (Dorren 2015); 3) our model, which is in development, mainly based on Wyllie's (2014) impact equations, with an imposed R_N limit of 2 (Noël et al. 2017); 4) the lumped mass model of the Colorado Rockfall Simulation Program (CRSP-3D v4) (Pfeiffer & Bowen 1989); 5) the lumped mass model of RocFall v6.0 software (RocScience Inc. 2018; Stevens 1998); 6) Wyllie's (2014) impact equations/observations without checking for energy conservation in between angular velocity and normal and tangential velocity.

We did not calibrate the parameters of the different models in order to obtain the best possible fit with the empirical data. Instead, we used mean values that correspond to the studied terrain materials, such as a used would do when limited data are available for calibration. The coefficients of restitution used were R_N of 0.35 and R_T of 0.85 for models 1), 4) and 5) (default bedrock outcrop); soiltype of 5 (for bedrock with thin weathered material or soil cover with R_N of 0.43 ± 10 %), Rg70 of 0.00, Rg20 of 0.05, Rg10 of 0.10 and block shape of 1 for model 2); model 3) as described in Noël et al. (2017). For model 5) the options to consider rotational velocity and to scale R_N by velocity were on, and the default variability of 0.04 standard deviation. was applied on the "coefficients of restitution" used as parameters.

Concerning the particle rotational velocity used in many models, instead of using the real angular velocity from the experiment as input values, which was not acquired, it was calculated using the equations of the respective models from the initial empirical conditions and the calculated outputs of the preceding impact.

5.2 Models vs. reality – preliminary results and evaluation

The results of the comparison are presented using the same four graphs as the ones analysed in section 4 (Figure 8). Comments about the different models are intentionally vague. We do not want to say that one model is better than another, especially knowing that their results could be different by choosing other parameters. These results are of interest for the community and a critical analysis will help improve our understanding and nourish discussion about the different models.

First, the models of of Dorren (2015), Noël et al. (2017), and Wyllie (2014) reproduce the non-linear distribution of R_N, unlike those of Stevens (1998), Pfeiffer & Bowen (1989), and Azimi & Desvareux (1977). Most R_N values of Dorren's model are above 1 and are quite scattered. It is surprising how different it is from Pfeiffer & Bowen's model values, since Dorren's model was mainly based on this second model. Without its probabilistic lateral deviation, Dorren's model gives apparent R_N and $\|\overrightarrow{v_{T2}}\|$ values almost identical to the latter one. On Pfeiffer & Bowen and Stevens models, the subtle effect of scaling their R_N parameters by velocity can be seen on their apparent R_N, unlike the Azimi model which does not use scaling.

Concerning their tangential apparent restituted velocities, they all exhibit linear trends, with more or less scattering. Dorren's model giving one the highest scattered values, which is near the amount of scattering observed with the empirical values.

The last column of graphs (Figure 8) summarizes the models behavior, by showing how much total velocity is restituted after an impact as a function of the 3D deviation. Here, Pfeiffer & Bowen and Stevens's models show a linear trend similar to the one observed, but with less deviation and slightly higher restituted velocities. Their values are also less scattered.

Dorren and Azimi & Desvarreux models both have total restitution in between 0.7 and 1.0. The first shows a lot of deviation, much more than the empirical values. Having more deviation and higher restituted velocities than observed isn't necessary a bad thing. It could help to produce conservative results when combined with low resolution digital elevation data. In the case of Azimi & Desvarreux model, the deviation is comparable to the one of Pfeiffer & Bowen and Stevens models.

The equations of Wyllie are not meant to be put together without considering the conservation of energy; this is why we observe here total restituted values greater than 1. Finally, Noël et al. (2017) model shows a similar distribution for the total coefficients of restitution as the empirical values, but with less deviation. Following this study and ongoing work, Noël et al. (2017) model has been improved and its development is continuing.

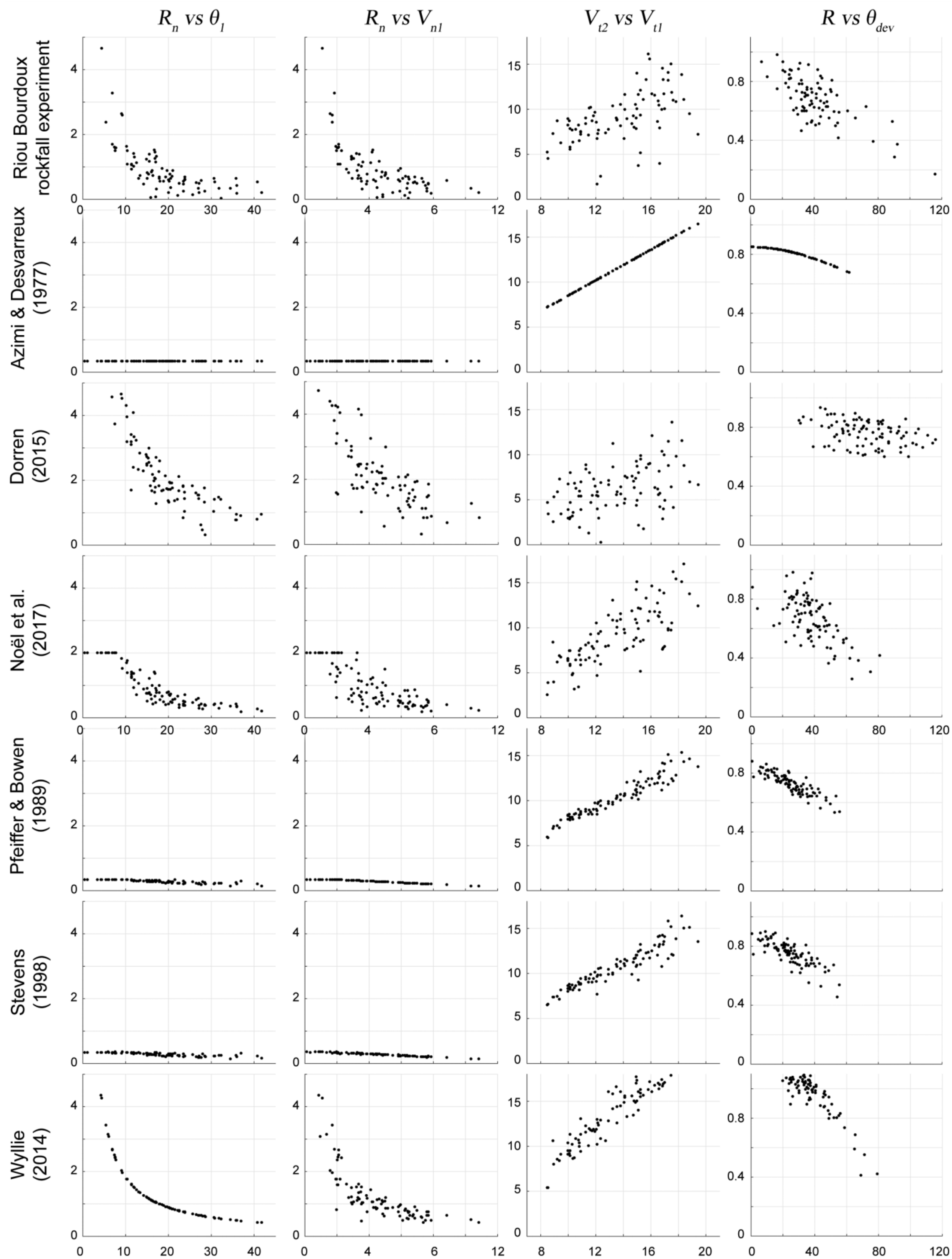

Figure 8. Comparison of the different rockfall impact models with real-size rockfall empirical values using the same four graphs as those previously seen in section 4. The reader is invited to pay a close attention to the last column, which summarizes the behavior for each model.

5.3 Fine tuning the impact models

As said previously, the outputted results of the models could be different by choosing other parameters; and finding the right set of parameters for rockfall simulations using most of these models is actually quite subjective because of the lack of data for calibration. However, now that we have these empirical data embedded with many rockfall simulation models in our Trajecto3D tool in development, the models can objectively be tested in 3D with the same input conditions than those noted from the real-size experiment.

We built a small interface to facilitate the interaction with those rockfall data, especially considering the fact that the database may grow. The user can click on each graph, choose which variables to display while trying to find correlations and adjust model's parameters to see which ones give the best fit over the empirical values. The models output values are displayed in red, linked to their corresponding empirical values with grey lines to help finding the best fit. Some of their parameters can be adjusted (eg. R_N, R_T, soiltype, the slope surface roughness, etc.), while seeing the effect on the outputted values in real-time.

The tool has been developed to facilitate the analysis of empirical data and to help making an informed choice of the parameters to be used with some rockfall simulation models. Also, because the models can be compared, finding equivalent parameters when multiple rockfall simulation programs are used in parallel should be easier. Ultimately, as the tool can easily be shared, it should improve practice and facilitate the teaching of rockfall hazards.

6 CONCLUSION

Some main advantages of the proposed method are: 1) 3D impact characteristics acquired using the method will become available to fill the gap where little data was accessible to fine tune parameters when using rockfall simulation softwares; 2) requiring only some cameras and a drone or a terrestrial laser scanner, the method is quite cheap to apply; 3) the method requires limited exposition and is quick to deploy, rockfalls in open-pit mines and quarry in exploitation could be studied to enhance the database without disturbing the operations. This new trajectory acquisition method allowed to compare objectively the different impact models used in softwares, which should help the community to make inform choices while simulating rockfalls. The developed tool combined with the rockfall database should facilitate the choice of the right parameters by allowing to see in real time the effect of the variables on the simulated results. Ultimately, this approach should improve calibration of rockfall simulation parameters, but also help to target which model is best suited for the given study. Of course, the given study site should be similar to the one from which the empirical values comes from. So feel free to contact us if you have empirical values to share or ideas for expanding the database!

7 ACKNOWLEDGEMENTS

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