DOI: 10.4408/IJEGE.2013-06.B-13

# TOWARDS THE COMPREHENSION OF ROCKFALL MOTION, WITH THE AID OF IN SITU TESTS

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## ABSTRACT

Rockfalls frequently occur in Alpine areas, creating serious risks to population and buildings; the protection measures against rockfalls cannot be adequately designed unless the comprehensive understanding of rockfall phenomenon. Some experimental rockfall tests have been performed on a talus slope in Grosina Valley (northern Italy), with the aim to check the reliability of common simulation methods and to analyse the motion of falling blocks. First, a-priori kinematic simulations have been performed, and, after the rockfall tests, the results have been compared with the real stopping positions of blocks. Afterwards, the recorded trajectories of falling blocks have been analysed, allowing the calculation of the motion parameters of falling blocks. The motion of blocks was mainly characterized by rebounds, therefore particular attention has been paid to restitution coefficients, which describe the loss of energy during the impact and greatly affect the results of rockfall simulations. Although the talus slope features are quite constant, an unexpected wide range of restitution coefficients results from the movies: the variability is greater than that one of bibliography, moreover normal restitution coefficients are extremely high (they often overpass the unit). The qualitative relationships between restitution coefficients and slope features, falling block characteristics and pre-impact motion conditions have been searched and described.

***Key words***: *rockfall, in situ test, restitution coefficients, kinematic simulations, Grosina Valley*

## INTRODUCTION

Rockfalls are very common and dangerous events in all mountain areas, due to their high motion velocities which render any warning equipments useless. A reliable forecast of trajectories, velocities, bounce heights and kinetic energies of potential falling blocks is fundamental in hazard mapping and territory management; although the prediction of motion parameters is a quite difficult task, because of their intrinsic randomness.

In the last twenty years, some methods and programs for the prediction of rockfall trajectories have been developed, but their applicability is restricted by the lack of numerous experimental data, concerning the parameters which govern the rockfall motion.

In this paper results of common predictive rockfall models, obtained applying kinematic simulations, have been compared with those obtained from experimental field tests, which have been carried out on an Italian talus slope. Firstly, geomechanical surveys of the release area of blocks have allowed recognizing the rock volumes prone to failure and the modalities of detachment. Afterwards the kinematic simulations of the blocks to test have been performed, using two different approaches and models.

On Alpine talus slopes, due to the high slope gradient, the motion of blocks is typically characterized by impacts and rebounds; therefore the most difficult task in kinematic simulation modelling is the choice of restitution coefficients (K), which quantify the loss of energy occurring during the impact.. These parameters are generally derived from literature, without the local specific outcropping material features are taking into account; indeed no standard methods exist to estimate K from field evidences. In the study area K values have been initially computed as the mean of bibliographic values; afterwards they have been calibrated, using a back-analysis approach, and used to perform kinematical simulations of blocks to test.

During the full scale in situ tests some coloured blocks, with different sizes and shapes, have been thrown down the slope by a caterpillar. The trajectory of each block has been recorded, the analysis of movies allowed to calculate, for each impact, velocities, K, energies, heights of bounce and impact angles. The comparison between forecasting models and the observed stopping points, as well as the measured motion parameters, is discussed in the paper.

## SETTING: THE AREA OF RESEARCH

The rockfall tests have been performed on a talus slope (0.13 km$^2$ extended), located on the left hydrographical side of the western Grosina Valley, an Italian Alpine valley, situated in Lombardy Region (province of Sondrio). Grosina Valley is a transverse of Valtellina and is a small glacial valley, with west-east orientation.

With regard to geological-structural context, this area pertains to the superior Austro-Alpine domain and is characterized by a thrust system which overlaps the Grosina-Tonale System, to the Campo-Ortles System. The former includes the Grosina Valley Formation, which outcrops in the study area and consists mainly of paragneisses and micaschists; the latter is mostly characterized by gneisses.

The left hydrographical side of Grosina Valley is affected by the Mount Farinaccio Slope Slide (Clerici *et alii*, 1994), which is a Depth Seated Gravitational Slope Deformation, 2 km$^2$ wide. The study area is situated on the external eastern-southern part of the Mount Farinaccio Slope Side.

In this area rockfall events sometimes occur, the last one happened in autumn 2010 involving numerous blocks. The release area of blocks is a steep cliff, about 70m high; its activity is witnessed by numerous fallen blocks, located along the slope, forming a talus slope which constitutes the transition and deposition zone of blocks. This scree cone, having a mean slope gradient of 35°, develops from the bottom of the cliff and, after two road crossings, reaches the Roasco River, at the valley floor (Fig. 1).

*Fig. 1 - The study area: a talus slope under a cliff in Grosina Valley*

The talus slope is characterized by a quite variable grain size, being a heterogeneous deposit, related to the superimposition of gravitational, glacial and, in the lower part alluvial events too; however large blocks are more frequent at the bottom of the slope and the cone can be classified as a fining-upward scree slope. The talus slope, with absence of trees, except seedlings in the lower part, forms a preferential corridor for rock blocks which fall down from the cliff and are free to reach the roads or also the Roasco River, as happened in autumn 2010. Laterally, beyond the cone, where the forest is present, the falling blocks fall stop behind trees, which are mainly spruces and larches.

## GEOMECHANICAL SURVEYS AND MARKLAND TEST

The release area of blocks is a cliff, having a dip direction which ranges from 170°, in the eastern part, to 290° in the western part, and a medium dip of 55°, which reaches also 80° in its higher part.

In spite of the difficulties due to the hard morphology and the general bad quality of the rock mass (which presents loosened fractures, often dislocated), geomechanical surveys have been performed in the source area, according to the ISRM suggested methods (I.S.R.M., 1977), with the aim to provide the quantitative description of the discontinuities in rock masses, which allows to, determinates both the features of the instable blocks and their detachment modality.

The outcropping lithology, belonging to the Mount Storile Paragneiss Unit, is a small grain paragneiss, with rare levels of quartz and amphibolite.

Four main discontinuity sets have been recognized and their properties measured.

The set called k1 develops almost parallel to the gneissic layering, with a sub-horizontal dip; the secondary joints have been subdivided in three main sets (k2, k3 and k4), whose representative orientations are reported in Table 1.

Along the line section, the intercept (i.e. the mean distance among different joints, independently of their orientation) is comprised between 6 and 20 cm, with values usually smaller than 50 cm, only one measure resulted slightly higher than 1 m. The mean spacing of discontinuities, which is very important to evaluate block volumes, ranges from 47 cm for k1 (the closest set) to 145 cm for k2 (the most spaced set). The persistence is high for both k1 and k2, medium for k4 and low for k3. Especially k2 and k4 sets, accompanied by k1, are responsible to isolate blocks, whose mean volumes are nearly 0.7 $m^3$ at the bottom of the cliff, but they increase towards the top until a medium estimated value of 1.5 $m^3$ due to the increasing of k1 spacing values going upwards; the maximum instable volume observed on the cliff has been estimated equal to about 20 $m^3$.

Almost all joints are without infillings, although they are vey opened: the average aperture reaches 1 cm for the closest set (k1), and 7 cm for the most open one (k2), whose values often exceed 10 cm; these wide apertures facilitate the detachment of blocks, as well as the smoothness of discontinuities planes, whose Joint Roughness Coefficient (JRC) ranges from 6 to 8, indicating very smooth discontinuities.

About the weathering conditions, joint walls seem to be only decolourized, except the set k2 which is slightly weathered, sure enough the average Joint wall Compressive Strength (JCS), determined using the Schmidt hammer, is about 58 MPa for k2, while it ranges from 70 to 77 MPa for all the other sets.

| Kind of discontinuity | Acronym | Dip | Dip direction |
|---|---|---|---|
| Gneissic planes | k1 | 2 | 236 |
| Joint | k2 | 73 | 130 |
| Joint | k3 | 76 | 60 |
| Joint | k4 | 76 | 238 |

*Tab. 1 - Mean values of dip and dip direction of the predominant discontinuity sets*

All joints were dry during the survey, even if it has been carried out in April and so during the snow melting period; only the set k2 shows oxidation traces, which can explain the greater weathering process suffered from this set.

The measurements of rock mass properties are very important to individuate not only the volumes of blocks, but also their predisposition to failure, which depends on the orientations of joints and slope face.

The dip and dip direction of gneiss bedding planes and joints (Tab. 1) has been measured by the compass.

With the aim to study the possible failure mechanisms, the Markland test (Markland, 1972) has been applied, plotting the great circles of the mean discontinuity planes detected on the cliff and comparing them with the circle of the peak friction angle along discontinuities, whose value, equal to 39°, has been computed applying the Barton & Choubey (1977) equation, with JRC and JCS values derived from geomechanical surveys. Adding the great circle of mean dip and dip direction of the cliff, it is possible to note that the failure of blocks can occur both for sliding and toppling of wedges. Indeed the point of intersection between k2 and k4 great circles lies between the friction angle circle and the great circle of the slope face. Furthermore the toppling phenomenon, can occur along k3, which has a dip close to slope dip, but the opposite dip direction. The analysis of each side of the scarp shows that the sliding of wedges predominates in the Eastern side of cliff, while the toppling occurs especially in its Western part.

The geomechanical survey assumes therefore a great importance to choose the initial modelling conditions (of block volumes and starting velocities, according to the detachment modality) in rockfall simulations.

## KINEMATIC SIMULATIONS

Kinematic simulations are a useful tool to study the propagation of blocks along a slope; these methods can be employed to forecast trajectories, bounce heights and energies of falling blocks. After the detachment, a block can continue its motion by free falling, bouncing, rolling and sliding. The free fall is modelled by the ballistic parabola physics law, knowing the initial velocities; after this phase, the block impacts to the soil, at the point described by the intersection between the trajectory of block and the slope surface. Then the block firstly rebounds and farther it can start to roll. The rebounds can be described using the normal and tangential restitution coefficients (Kn and Kt), expressed by the ratio between the velocity after and before the impact, respectively normal and tangential to the slope. Kn and Kt quantify the loss of energy which occurs during impacts, and their values depend basically on the outcropping material and the presence of obstacles. On the apex and on the upper part of the talus slope, as a whole, the motion can be simulated using rebound models, which can be separated in two types: lumped-mass and rigid body approaches; the former models the block as a single material point, the latter accounts for the block shape. In this study, both methods have been tested.

Whatever is the simulation approach chosen, a big influence on the results is given by the topography, the more it is accurate, better the results will be. Two different approximations of the slope topography exist: the 2D slope profile and the 3D grid, which typically is a rasterized Digital Elevation Model (DEM).

In this research the software Rotomap (Scioldo, 1991) and Colorado Rockfall Simulation Program (CRSP, Pfeiffer & Bowen, 1989) have been used, the former employs the lumped-mass approach, with a 3D grid, while the latter utilises the rigid body model, with a 2D section. Unluckily, as it often happens, the detailed topographic base of Mount Farinaccio has not available, but only the DEM with 10m resolution, consequently, Rotomap has been initially employed, being a 3D model well-adaptable for studies at regional scale with also a smoothened topography (Ferrari *et alii*, 2011). Afterwards a section along the maximum dip angle, located in the centre of the talus slope, has been chosen and used to model in 2D the rockfall, with CRSP; this section should be the most critical of the whole talus slope. In addition, also the most dangerous section derived from Rotomap results, has been individuated and compared with the a priori chosen section.

The Rotomap software, physically based, models rockfall process in 3D, adopting the lumped-mass approach: the falling boulder is considered dimensionless (i.e. a point). In addition to the topography, the input data include some parameters related both to the detachment of blocks (location of release areas, number and mass of blocks to simulate, starting velocities and angular deviations), and to their motion: limit angles, restitution and of dynamic rolling friction (μ) coefficients, which are used to simulate the loss of energy during bouncing and rolling, respectively.

CRSP is a commercial software, which performs rockfall simulations along an user defined topographic profile, adopting a rigid-body approach and so taking into account also the shape of blocks (always with circular sections), and their dimensions. Also this program requires the input data relative both to the detachment points and the motion parameters (K and μ), adding the roughness (ε).

Whilst the input data related to block geometries and detachment points can be easily gathered by topographical, geomechanical surveys and also photogrammetrical analysis, those related to motion are particularly difficult to infer, in fact neither direct field procedures nor empirical correlations exist to estimate these parameters, which can be derived performing in situ rockfall tests. If rockfall tests cannot be performed, motion coefficients can be hypothesized, arising from bibliographical values, or back-calculated, analysing the past rockfall events occurred in the area; this last procedure can be applied only if the stopping positions of fallen blocks are exactly known, numerous problems arise when the blocks have been removed or buried, without mapping their locations.

Since motion parameters depend basically on the outcropping material and the presence of obstacles, it is a common practice to subdivide the study area in some homogenous regions.

Hence the studied area has been divided in zones (Fig. 2), on the basis of the outcropping substratum and the presence, density and kind of vegetation cover; at each zone motion parameters (Kn, Kt, μ and ε) have been assigned.

In the first set of kinematic simulations motion coefficients have been derived averaging out bibliographic values, obtained in similar geological and geomorphological contexts (Piteau & Clayton, 1987; Azzoni *et alii*, 1992; Clerici & Sfratato 2004; Giani *et alii*, 2004; Ferrari *et alii*, 2011). The resulting stop-

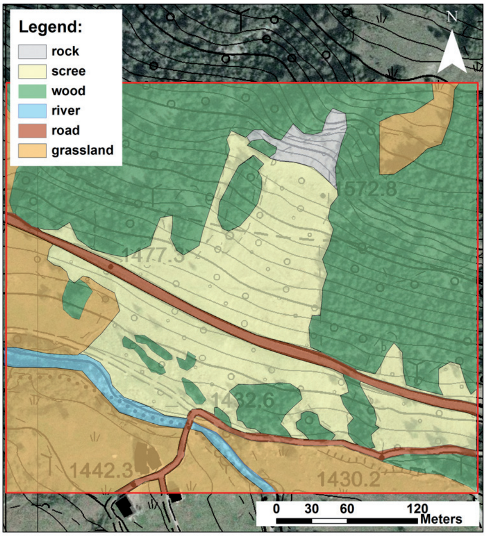

*Fig. 2 - The modelled domain subdivided in units, on the basis of the outcropping substratum and the presence and kind of vegetation cover*

ping points are located farther than blocks fallen down in the study area in autumn 2010. Indeed in the simulations all blocks have reached the Roasco River and some of them have been able to go up the slope beyond the river (Fig. 3a), while during the 2010 event some blocks stopped on the road and on a terrace situated at the bottom of the cliff, which had been deliberately created to hold the falling blocks. It follows that the bibliographical values, although carefully selected from similar contexts, should always be calibrated (Ferrari *et alii*, 2012), using the back-analysis approach. In order to shorten the travel distances of blocks, Kn and Kt have been reduced, while ε has been raised (Tab. 2). The back-calculated parameters obviously fit well with the stopping points of the 2010 event (Fig. 3b).

| | *bibliography* | | | | *back-analysis* | | | |
|---|---|---|---|---|---|---|---|---|
| *Unit* | **Kn** | **Kt** | **μ** | **ε** | **Kn** | **Kt** | **μ** | **ε** |
| Rock | 0.57 | 0.73 | 0.64 | 0.35 | 0.60 | 0.80 | 0.20 | 0.35 |
| Scree | 0.41 | 0.65 | 0.62 | 0.30 | 0.40 | 0.63 | 0.65 | 0.60 |
| Wood | 0.28 | 0.49 | 0.73 | 0.90 | 0.20 | 0.40 | 0.70 | 0.90 |
| River | 0.30 | 0.65 | 0.60 | 0.40 | 0.20 | 0.40 | 0.60 | 0.70 |
| Road | 0.40 | 0.90 | 0.55 | 0.05 | 0.40 | 0.90 | 0.20 | 0.45 |
| Grassland | 0.29 | 0.48 | 0.58 | 0.15 | 0.40 | 0.50 | 0.30 | 0.35 |

*Tab. 2 - Motion parameters assigned to homogeneous units, derived both from literature and site-specific back-analysis approaches. Kn and Kt are respectively the normal and the tangential restitution coefficients, μ is the dynamic rolling friction coefficient and ε the slope roughness*

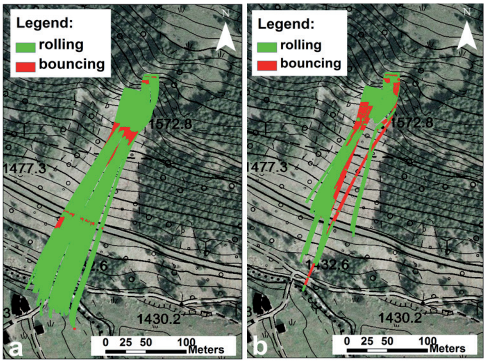

*Fig. 3 - 3D paths of the falling block obtained from literature (a) and back-analysis (b)*

Although the calibration of coefficients on the specific investigation site plays a key role in modelling, it cannot be done in areas where the previous events are mainly unknown and their features not identifiable. If only the stopping points of blocks are known, but not the precise location of the release areas (such as in the case of study), cautionary results have been obtained using the bottom of the cliff as the source point. An ulterior problem in the calibration is related to the fact that, if several homogeneous units are involved, infinite different combinations of motion coefficients will lead to the same stopping positions, implying a big uncertainty in the calibration of models based only on the stopping points of blocks. This uncertainty could be reduced considering the silent witnesses, i.e. the signs produced by the passage of blocks (tree and surfaces hits), which allow to reconstruct the travel path of the block and its features. This process cannot be applied in the study area, being these signs neither well identifiable nor attributable to a specific block. So in order to evaluate the uncertainty related to the calibration process, the results of simulations have been compared with those of the in situ tests, performed in May 2011. These tests have been carried out with the aim to remove some instable blocks stopped on the terrace at the bottom of the cliff during the last rockfall event, therefore the sizes and shapes of blocks to test were exactly known, as well as their precise starting location. Using these initial motion condition and the back-calculated motion coefficients, a new set of kinematic simulations has been performed, before the test execution.

## IN SITU TESTS

The sizes and shapes of blocks to test have been carefully chosen among those lying on the terrace. Considering geomechanical survey results, priority has been given to rocks with a nearly parallelepiped shape and volume approximately equal to almost 0.8 $m^3$, being the mean volume of blocks which were able to reach the road during the 2010 event. Each block has been measured along its three dominant axes, making possible the calculations of volumes and masses. The block volumes are in good accordance with the volumes computed from geomechanical survey data, although the spacing of the set k1 is slightly underestimated.

Before the tests, a graduated rope has been fixed along the slope as metric reference, and blocks have been painted using different colours with the aim to allow their recognition during and after the tests.

During the tests the chosen blocks have been pushed down the slope by a caterpillar. The trajectory of each block has been recorded using both lateral fixed cameras and a frontal mobile one. The lateral cameras have recorded the block movements in the upper part of the talus slope, and the frontal camera the entire path.

The blocks started from a static position by rolling and then began their descendent. Afterwards they either continued to roll or mainly took one two bounces and went into flight. If the stone was larger than the materials over which it moved, its angular momentum increased until two basic factors began to diminish its velocity: a flatter portion of the slope, and larger materials of substratum (Ritchie, 1963). As the rolling stone met material of its own size, it began to collide against common pieces, losing energy. With this deceleration process, the stone was soon trapped in voids between stones of its own size, resulting in a segregation of materials, observed on the talus slope.

The precise stopping positions of blocks have been measured by Global Position System and compared with simulation results.

### *COMPARISON BETWEEN STOPPING POSITIONS AND THEIR PREDICTION THROUGH SIMULATIONS*

According to the Italian regional law on rockfalls (Regione Lombardia, 2006), on the basis of simulation results, the study area has been zoned into preliminary hazard classes H4, H3 and H2, related respectively to the passage and stop of the 70%, 95% and 100% of falling blocks. In the 3D model all blocks, which have not been subject to fragmentation along their paths, have stopped in the area individuated as hazard class H4, whilst the fragments of blocks, have been able to reach farther location than those forecasted by simulations, although they have been carried out with 1000 blocks, knowing the precise starting position and dimension (or mass in lumped-mass method) of blocks.

The distances obtained by the 2D model are a little overestimated, it could due to the fact that the steepest profile has been taken into account; moreover in CRSP all the blocks have a circular section, while in reality they have prismatic sections, and so a smaller motion efficiency.However the results of the back-analysis process revealed to be very useful and reliable to forecast the trajectories of blocks, but more efforts should regard the problem of block fragmentation and especially the angular deviation of fragments.

The main limitation of this approach is that this comparison, as well as the classical back-analysis process, takes into account only the stopping positions of blocks, without considering their kinematic, which can be evaluated using both field experiments and laboratory tests, although the latter are difficult to extend to field processes due to the difficulties encountered when defining similitude rules (Bourrier *et alii*, 2012).

### *DETAILED ANALYSIS OF MOTION*

In order to analyse the motion and the kinematic parameters developed by the blocks during their paths, the lateral videos have been studied frame by frame, extracting 30 frames per seconds. The frames have been referenced in the space, using the graduated rope fixed along the slope, through the distance among known points. In each frame the barycentre of falling block has been individuated, as a point, and the set of points represents the trajectory of the block (Fig.4). The points have been initially referred to the global $xy$ Cartesian coordinate system, where $x$ is the horizontal axis and $y$ is the vertical axis; afterwards a second (local) $nt$ system has been determined, with direction $n$ normal and $t$ tangential to the slope surface. Knowing both the coordinates of barycentres and the interval of time $\Delta t$ between two following frames, the displacements of barycentre $S$ and the translational velocity $V$ vectors (in terms of direction and magnitude) have been calculated along the path of block.

*Fig. 4 - The trajectory of a block, obtained from frame by frame analysis*

The translational pre-impact and post-impact velocities, normal and tangential to the slope, have been computed applying the following formulas (*et alii*, 2002):

$$Vn_{pre} = \left( \frac{\Delta Sy}{\Delta t} + \frac{1}{2} g\Delta t \right) \cos\alpha - \frac{\Delta Sx}{\Delta t} \sin\alpha$$

$$Vt_{pre} = \left( \frac{\Delta Sy}{\Delta t} + \frac{1}{2} g\Delta t \right) \sin\alpha + \frac{\Delta Sx}{\Delta t} \cos\alpha$$

$$Vn_{post} = \left( \frac{\Delta Sy}{\Delta t} - \frac{1}{2} g\Delta t \right) \cos\alpha - \frac{\Delta Sx}{\Delta t} \sin\alpha$$

$$Vt_{post} = \left( \frac{\Delta Sy}{\Delta t} - \frac{1}{2} g\Delta t \right) \sin\alpha + \frac{\Delta Sx}{\Delta t} \cos\alpha$$

where $g$ is the gravitational constant (i.e. $9.81 m/s^2$) and α is the slope angle close to the impact point.

Since in the upper part of the talus slope, where lateral cameras have been placed, the rebound is the predominant kind of motion, Kn and Kt have been computed, as the ratio between translational velocities (normal and tangential to the slope respectively) after and before the impact.

The computed values (Fig. 5) are very scattered and show a greater variability than that of the literature. Nevertheless Kt values are in quite good accordance with common bibliographic values for bare talus slopes, which generally range from 0.55 to 0.80, whilst the computed Kn values are extremely high, with a mean value bigger than one, although the unit is often seen as an upper boundary for K in numerical codes. Actually, K equal to one corresponds to a perfect elastic collision, K below one defines an inelastic collision, and K nought means that the block instantaneously stops at the surface without bouncing, with a perfectly plastic behaviour (Goldsmith, 1964). As consequence, K above one should mean that the block gains translational velocity during the impact, which is unlikely. Nevertheless experimental evidences show that Kn values above the unit sometimes occur, being measured both in field tests (Azzoni *et alii*, 1992; Bourrier *et alii*, 2009; Bourrier *et alii*, 2012; Spadari *et alii*, 2012; Asteriou *et alii*,2012) and in laboratory (Buzzi *et alii*, 2012; Asteriou *et alii*, 2012). So high Kn values have been also calculated by simulations (Bourrier *et alii*, 2009) and back-analysis approach (Paronuzzi, 2009). It is therefore necessary to find an explanation for the occurrence of so high Kn values.

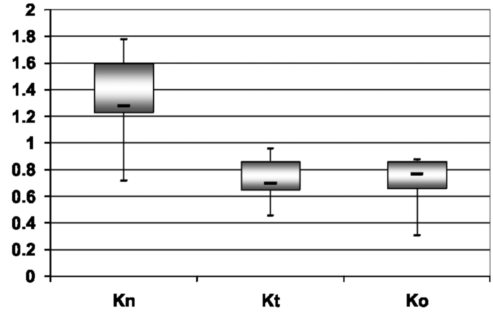

*Fig. 5 - Box-plots of normal (Kn), tangential (Kt) and overall (Ko) restitution coefficients, calculated from Grosina Valley in situ tests*

Considering the results obtained from Grosina Valley test site, although Kn values are often above one, if the overall K (Ko) is computed, as the ratio between the post- and pre-impact total translational velocities (without considering the factorization in normal and tangential velocities), it results always below one, which is coherent with the energy dissipation occurring during the impacts. Kn values higher than the unit can therefore occur, provided that Ko is smaller than the unit.

The main explication to obtain Kn above the unit is related to the geometric relationship between the block and the slope during the impact, and to the rotational motion established at the impact point. Actually applying the law of the conservation of energy, it is possible to see that the impact causes the increasing of the rotational energy (between the 3 and 16% of the total energy) at the expense of the translational total energy, which has components related to the velocities tangential and normal to the slope. While the contribution of the former, after the impact, always decreases (between the 8 and 35%), the latter increases (between the 4 and 19%).

High Kn values have been measured especially for blocks with high anisotropy ratio, sure enough a lengthened block, if impacts with its major axis about perpendicular to the slope, rotates and its barycentre becomes higher than those of a block which impacts with the major axis almost parallel to the slope. Actually the barycentre of a lengthened block is subjected to a bigger displacement in the direction normal to the slope than that of an equilateral one. If a lengthened block impacts with its corner, the arm of the angular velocity along the direction normal to the slope can be strongly greater than the arm of the angular velocity along the direction translational to the slope and consequently Kn can overpass the unit, even though the loss of kinetic energy produced by the impact is saved (Ferrari *et alii*, 2013).

Additionally high Kn values seems to be linked with small grain size of the outcropping material, high slope angle, and consequently small incidence angle (in this study Kn above the unit has been measured with incidence angle smaller than 15°). Actually steeper the slope is, smaller the impact angle will be, hence Kn increases with the decrease of impact angle or equally with the increase of slope angle. Moreover smaller the normal translational impact velocity is, higher Kn will be (in this study Kn above the unit has been measured with normal impact velocity below 10 m/s).

## CONCLUSIONS

This paper describes some in situ rockfall tests, carried out on an Italian talus slope, and the comparison between kinematic simulations and test results.

The initial motion conditions have been inferred from geomechanical surveys, which allowed to calculate unitary rock volumes prone to failure, and to individuate the possible detachment mechanisms. The motion parameters firstly have been calculated averaging out the literature values, and then they calibrated through a back-analysis process, this step has revealed to be of fundamental importance. The so derived motion parameters have been used to simulate the falling of the blocks selected for the tests. The comparison between a-priori simulation results and real stopping points of tested blocks are close only if the block is not subject to fragmentation during its paths. The 2D model, with rigid-body approach, has proved to be more cautionary than the 3D lumped-mass model.

Afterwards the motion parameters and in particular the restitution coefficients have been calculated by test movies, using image analysis techniques. The resulting tangential restitution coefficients agree with literature, whilst the normal ones are uncharacteristically high (often above the unit). So high normal restitution coefficient are mainly related to the geometry of the block at the impact point, but also to the outcropping material grain size, slope angle and to parameters linked with the kinematics of block before and during the impact.

Moreover both restitution coefficients resulted to be very scattered, although they have been measured in an area with the quite constant features (a bare talus slope). These coefficients change within the same homogenous unit, going downward the slope. Therefore the common practice in rockfall modelling which considers motion parameters constant inside each homogenous area has proven to be too much simplistic. Inside each homogenous zone it should be better to consider not a constant value but a range of variation of these coefficients. Additionally the subdivision in homogenous areas should be more detailed, considering also small grain size and slope angle variations, which have proven to affect the restitution coefficients.

With the aim to improve the modelling some efforts could be done to study the fragmentation phenomenon and to find the quantitative relationships to estimate the restitution coefficients from field evidence.

## ACKNOWLEDGMENTS

The authors would like to thank: Giovanni Di Trapani and “Comunità Montana di Tirano” for the possibility to perform the tests, Erika De Finis and Andrea Merri for the help during field surveys, but also Alessio Conforto and the Professor Marco Masetti.

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