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Why can rockfall normal restitution coefficient be higher than one?

FEDERICA FERRARI (*), GIAN PAOLO GIANI (*) & TIZIANA APUANI (*)

RIASSUNTO

Perché nell'analisi del moto di caduta massi il coefficiente di restituzione normale può essere maggiore di uno?

La modellazione del fenomeno di caduta massi è solitamente svolta con l'ausilio di simulazioni cinematiche, che consentono di calcolare le traiettorie dei blocchi potenzialmente instabili. Sui pendii molto acclivi i risultati sono fortemente influenzati dal valore dei coefficienti di restituzione, che quantificano la dissipazione di energia durante l'impatto; poiché l'urto blocco-pendio è prevalentemente anelastico, tali coefficienti dovrebbero sempre essere minori di uno. Tuttavia evidenze sperimentali mostrano l'occorrenza di valori superiori ad 1 nella direzione normale al pendio. La presente nota analizza le relazioni che intercorrono tra i coefficienti di restituzione e le caratteristiche del pendio, del blocco e del moto di caduta, partendo da prove in situ svolte in Val Grosina (SO).

KEY WORDS: *In situ test, restitution coefficients, rockfall.*

INTRODUCTION

Rockfall consists of detachment of blocks from a cliff face, with subsequent free-falling, bouncing, sliding and rolling motion. Because of high motion velocities, rockfalls are among the most dangerous phenomena in all mountain areas, and pose serious hazards to residential areas, roads and population.

To reduce rockfall hazard, mitigation techniques have been widely used, their design is based on the estimation of trajectories, bouncing heights and the kinetic energies of the instable blocks. These parameters can be obtained through the use of kinematic simulations which nowadays are one of the most popular approaches in rockfall hazard assessment.

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

In this paper results of experimental field tests carried out on a scree slope, located in Northern Italy, are presented. On Alpine talus cones the motion of blocks is typically characterized by impacts and rebounds, which in modelling are described using two phenomenological coefficients: the restitution coefficients (BOZZOLO & PAMINI, 1986; PITEAU & CLAYTON, 1987). These parameters quantify the loss of energy which occurs during the impact and therefore are among the most crucial input data controlling the rockfall hazard.

(*) Dipartimento di Scienze della Terra "Ardito Desio", Università degli Studi di Milano. federica.ferrari@unimi.it

The restitution coefficient (*K*) is expressed by the ratio between the post-impact and pre-impact velocities, subdivided in components tangential (*Kt*) and normal (*Kn*) to the slope. Theoretically, when *K* is equal to zero the block instantaneously stops at the surface without bouncing, with a perfectly plastic behaviour; when *K* is lower than the unit, it defines an inelastic collision, and finally the unit value corresponds to a perfect elastic collision (GOLDSMITH, 1964). It follow that the unit is often considered the upper boundary, because of energy dissipation which should occur during the impact. Nevertheless the analysis of *Grosina* Valley rockfall test movies shows *Kn* higher than the unit, so high *Kn* values have already been measured both in field tests (AZZONI *et alii,* 1992; BOURRIER *et alii,* 2009; ASTERIOU *et alii,* 2012; BOURRIER *et alii,* 2012; SPADARI *et alii,* 2012;) and in laboratory (ASTERIOU *et alii,* 2012; BUZZI *et alii,* 2012), and also calculated by simulations (BOURRIER *et alii,* 2009) and by back-analysis approach (PARONUZZI, 2009).

GEOGRAPHICAL AND GEOLOGICAL CONTEXT

The rockfall tests were performed on a scree slope located on the left hydrographical side of the *Grosina* Valley (province of *Sondrio*), a small glacial valley transversal to the *Valtellina*.

The study area pertains to the superior Austro-Alpine domain and is characterized by the presence of a thrust system that overlaps the *Grosina-Tonale* System to the gneiss of *Campo-Ortles* System. The former includes the *Grosina* Valley Formation, whose member called "paragneiss of *Storile* Mount" outcrops on the steep cliff, about 70 m high, which constitutes the source area of blocks in the study area. The scree cone develops from the bottom of the cliff until the *Roasco* river, with a mean slope gradient of 35° and an extent of 0.13 km^2. The cone is characterized by a quite variable grain size, being an heterogeneous deposit related to the superimposition of gravitational, glacial and alluvial events. However blocks are more frequent at the bottom of the slope and granulometric analyses show a fining-upward trend. The cone, with absence of trees, except seedlings at the bottom, forms a preferential corridor for the falling blocks. Laterally the cone is bordered from a wood of spruces and larches.

IN SITU TESTS

Experimental rockfall tests were performed with the aim to remove some of the blocks which fell off in Autumn 2010 stopping at the top of the cone, on a small terrace, which was expressly built for rockfall protection. The sizes and shapes of blocks to use were carefully chosen among blocks lying on the terrace, giving priority to those with a nearly parallelepiped shape and a volume approximately equal to $1m^3$, being the critical mean volume of blocks which were able to reach the road, located at the bottom of the cone, during the 2010 event.

A graduated rope was fixed along the slope as metric reference, and the blocks were painted using different colours to allow their identification during and after the tests. The selected blocks were pushed down the slope one by one using a caterpillar, and the trajectory of each block was recorded using both lateral fixed cameras, placed along the slope, and a frontal mobile one. The lateral cameras allowed to record the block movements in the upper part of the slope, while the frontal camera recorded the entire path of blocks.

DETAILED ANALYSIS OF MOTION

A selection of the useful impacts, among the whole videos, have been performed in order to reduce the errors. The videos wherein the block assumes the equivalent rolling motion (i.e. with aerial rotation and multiple collision on the slope), or wherein rockfall path is not approximately parallel to the camera have been rejected. The resulting useful rebounds, with a well-identifiable impact point, are ten for the higher camera and five for the lower one, since some blocks broke or started to roll.

The selected videos have been analysed, extracting 30 frames per second. The displacements of falling block barycentre, determined as a point in each frame, allowed to calculate, for each impact, the translational velocities. The series of points defines the block trajectory. Initially the points have been referred to the global *XY* Cartesian coordinate system, where *x* is the horizontal axis and *y* the vertical one; afterwards a second (local) *nt* system has been calculated, where *n* is the direction normal to the slope and *t* the tangential one. By knowing the coordinates of the barycentre, and the time Δt between two following frames, it has been possible to calculate the displacement ΔS and the translational velocity *V* vectors (in terms of direction and magnitude) of the block centroid along the path (GIANI *et alii,* 2004). The translational pre-impact and post-impact velocities, normal and tangential to the slope, have been calculated applying the following formulas (CHAU *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 ΔSx and ΔSy are the displacement components in the *XY* system in the interval time Δt, *g* is the gravitational constant (i.e. 9.81 m/s^2) and α is the slope angle close to impact point.

Afterwards, considering the mean values of the four frames before and after the impact, *Kn* and *Kt* have been computed as the ratio between post- and pre-impact velocities. The resulting *Kn* and *K*t values are very scattered and show a greater variability than those of rockfall literature. While Kt values are in quite good accordance with well-known values for bare talus slopes, which generally range from 0.55 to 0.80, *Kn* values are extremely high if compared to the common bibliographical values, which range from 0.25 to 0.65. Computed *Kn* often results grater than the unit, with a medium value of 1.78, this means that the block should gain normal translational velocity during the impact, which is unlikely. It is worth to note that if the overall *K (Ko)* is computed, considering total translational velocities, without the factorization into normal and tangential velocities, it results always below 1, which is coherent with the energy dissipation of mechanism, which occurs during the impacts. As consequence local *Kn* values higher than the unit can occur, provided that *Ko* is smaller than the unit.

An attempt to correlate *K* with the main slope, block and motion features has been done. Indeed it should be very useful to find quantitative relations to estimate *K* from field evidence, e.g. considering the characteristics of the local outcropping materials and of the blocks prone to failure. Although it is well-known that the values of *K* depend basically on material type and slope roughness, no standard methods exist to estimate them. Generally *Kn* and *Kt* are derived from literature, but this method has proven to be unreliable, though selecting values from a morphological and lithological context similar to the investigated area (FERRARI *et alii,* 2012). Better results come from the calibration of *K* by a back-analysis approach, based on the stopping points of previous rockfall events, but this method can be applied only if the stopping positions of blocks are exactly known.

Generally to perform kinematic simulations the studied area is subdivided in zones with homogenous characteristics of substratum and vegetation. At each on these zones a constant value of *Kn* and *Kt* is ordinarily assigned, but this approach seems to be too much simplistic, indeed the test results show that, although considering lateral cameras placed in the same homogeneous area, *K* reduces going down the slope. With an high difference between two cameras of 25m, the mean values of *Kn*, *Kt* and *Ko* reduce respectively of 20%, 7% and 1%. It can be related both to the increase of grain size (from SW to GW, according to the Unified Soil Classification System, ASTM, 2006) and to the reduction of slope angle (from 35° to 30°). It results that the division into homogenous areas should be more detailed than the common practice, indeed also small grain size and slope angle variations should be investigated and counted for, since bigger the grains of the outcropping material are, higher the roughness is and therefore lower *K* is. Moreover despite the same outcropping material, steeper the slope is, higher *K* is.

The block features and in particular the weight, computed knowing the block shape and dimensions, seems not affect *Kn*, but bigger the mass is, higher *Kt* is. It is reasonable, since for larger blocks the effective surface roughness is lower than for smaller rocks (DORREN *et alii*, 2004). Regarding the block dimensions, high *Kn* values are related to high anisotropy ratio, actually during the impact the block rotates and its barycentre is subjected to a bigger displacement in the direction normal to the slope than that of an equidimensional one.

The pre-impact motion features have been also considered. It is well-known that *Kn* values higher than the unit are related to small incidence angle (<15° in this study), while *Kt* has no simple correlation with this angle. It is important to note that for steep slope the impact angle is always small. *Kn* increases with the decrease of impact angle or equally with the increase of slope angle.

Another parameter which affects *Kn* is the normal translational impact velocity: smaller it is, higher *Kn* is. In this study *Kn* higher than the unit occur with normal impact velocity below 10m/s.

The principal explication for obtaining *Kn* greater than the unit seems to be connected to the geometry of the block during the impact and to the rotational motion established in the impact point. High *Kn* values are related to lengthened blocks which impact with the major axis almost perpendicular to the slope, hence, with the rotation of the block, the barycentre is higher than those of a block which impacts with the major axis parallel to the slope. Nevertheless also in this last case *Kn* is overestimated, because the impact is not a point but an area, moreover a sliding phenomenon is sometimes observed, before the rebound. Higher the contact area is, lower *Kn* is. If a lengthened block impacts with its corner, and so if the impact is punctual, the arm of the angular velocity along the *y* direction can be strongly greater to the arm of the angular velocity along the *x* direction and consequently *Kn* can overpass the unit, even though the loss of kinetic energy produced by the impact is saved.

CONCLUSIONS

This paper describes the methodology of some in situ tests, carried out on an Italian scree slope, and the modality to calculate restitution coefficients from image analysis. The resulting *Kt* agrees with literature, although with an higher scatter, whilst unusual high *Kn* occurred during the tests.

The detailed analysis of motion shows that *Kn* does not depend only on the slope material characteristics, which are usually taken into account, but also on the slope angle and on parameters related to the falling block characteristics (weight, size and shape) and to the kinematics before the impacts (impact velocity and incidence angle) and during the impact (position, rotation and contact area).

The common practice in rockfall modelling considers *Kn* and *Kt* constant inside homogenous areas, subdivided only on the basis of the outcropping material and vegetation, and therefore can lead to unreliable results. The modelling approach can easily be improved considering a more detailed discretization in homogeneous area, which should take into account also small grain size and slope angle variations. Moreover for each detailed area not a constant value but a range of restitution coefficients should be assigned.

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