15th International Congress of the Geological Society of Greece
Athens, 22-24 May, 2019 | Harokopio University of Athens, Greece
Bulletin of the Geological Society of Greece, Sp. Pub. **7** Ext. Abs. GSG2019-006

A semi-empirical approach for the prediction of trajectories in rockfalls

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Rockfalls constitute a significant natural hazard that manifests as a sudden and violent downward movement of rock blocks. The design and implementation of appropriate mitigation measures rests on the estimation of the possible trajectories. Once the block comes in contact with a slope, depending on the kinematic state and the contact geometry, it might rebound resulting in a new parabolic trajectory. Alternate response types to rebound are rolling, sliding or a combination thereof. The rebound, which controls the post-impact part of the trajectory, is calculated according to the coefficients of restitution (COR) which are overall values that take into account all of the characteristics of the impact and describe the change in the block's velocity magnitude. Normal COR (n_{COR}) is defined as $n_{COR}=-v_{nr}/v_{ni}$, and Tangential COR (t_{COR}) is defined as $t_{COR}=v_{tr}/v_{ti}$, where *v* is the velocity and the subscripts *n*, *t* define its components (normal and tangential to the slope surface respectively), whereas as the subscripts *i* and *r* denote the impact and rebound stage.

COR estimation in practical applications is based on some suggestive values, which depend solely by the slope surface material. In addition, CORs are adjusted to the impact velocity applying some scaling methods that are also empirically derived. A detailed overview of COR definitions, suggested COR values and the scaling methods can be found in Asteriou & Tsiambaos (2018). However, the rebound is affected by many parameters: (i) the strength, stiffness, roughness and the inclination of the slope; (ii) the strength, stiffness, mass and shape of the block, and; (iii) the translational and rotational velocity, the collision angle and the configuration of the block during impact (Labiouse & Heidenreich, 2009). Therefore, selecting the COR values just by the material type consisting the slope can lead to significant simplifications.

It becomes apparent that a better method for selecting the COR is necessary. To attain this necessity, a semi-empirical method is presented hereafter, which considers: (i) the material types of both the slope surface and the block; (ii) the block mass and its incident velocity, and; (iii) the collision angle.

Methodology

An extensive experimental study was designed in order to examine the COR values with respect to the aforementioned parameters and to establish a correlation between them. The equipment required for conducting impact tests in the laboratory includes a block, an impact surface, a release mechanism and a data acquisition system.

Block shape has been found to have a significant effect on the rebound trajectory due to the configuration of the block at impact (Asteriou & Tsiambaos, 2016). When the block has an irregular shape, the impact configuration varies significantly between tests, introducing stochastic effects. To eliminate these effects, the tests were performed using spherical blocks and flat impact surfaces. The blocks were cast in silicon molds by two different artificial materials, namely a high-strength cement grout and an epoxy resin, with diameters of 3, 4, 5 and 6cm. Additionally, blocks were formed from intact specimens of a fine-graded marble and a quartzic sandstone, with diameters in the aforementioned range. Impact surfaces were created for all materials used. Each impact surface was the top side of a 5-cm-thick rectangular plate with 15cm sides that was fixed to a massive dead weight base to ensure the preservation of momentum during the impact. The physical and mechanical properties of these materials were determined according to the ISRM suggested methods, in order to correlate them with the response of the blocks at impact.

Two release mechanisms were developed. The first was used to conduct free-fall tests and consisted of an arm that held the block in the desired height by suction that was produced from a vacuum pump. The second mechanism involved an inclined tube with adjustable length and inclination, so as to control the incident translational velocity and the collision angle. The block was inserted into one side and released from the other towards the impact surface, after sliding and rolling through the tube, which also generated a random angular velocity.

The trajectories were recorded with a high-speed digital video camera at a frame rate of 500fps and a resolution of 440×330 pixels. The camera was installed 1m from the impact surface. A high-contrast background was installed to make the block visually distinguishable. An in-house machine vision algorithm was developed to track the motion and analyse the trajectory, providing all the necessary experimental data.

In total, over one thousand impact tests were performed organised in three stages. In the first stage, in order to assess the effects of material type, block mass and incident velocity, blocks from all material types and all sizes were released by free-fall, from various heights to impact on surfaces consisting of the same material. In the second stage, similar tests were performed, but the blocks impacted on surfaces of a different material type to assess the effect of impacts between different materials. Finally, in the third set, oblique impact tests were performed to study the effects of the collision angle and the angular velocity. A detailed documentation of the aforementioned testing campaigns (apparatuses, procedure, material properties, data acquisition and results) can be found in Asteriou & Tsiambaos (2018) and Asteriou (2018).

Research outcomes

In the first stage, the free-fall drops were performed from heights ranged from 0.1 to 4.5m, resulting in incident velocities (v_{ni}) ranging from 1.3 to 9.3ms^{-1}. Irrespectively of the material type, the results indicated that n_{COR} reduces with an increase in incident velocity and that for a given v_i, an increase in mass decreases n_{COR}. However, the rate of change differed for each material tested, indicating that the rebound is also affected by the material type. A significant correlation was extrapolated when assessing the n_{COR} values, derived from the experimental testing, with the incident momentum (M_{ni}). The response (Figure 1) was well described by a hyperbolic function of the form:

$$n_{COR} = f(R)M_i^a + 1 \qquad (1)$$

where R is the Schmidt hammer hardness value, which has been found to be the material property that correlates better with n_{COR} (Asteriou *et al.*, 2012). This was anticipated since the mechanical analogues of both the Schmidt hammer test and the free-fall impact tests resemble many similarities.

Eq.1 yields one when the incident momentum is very low, which corresponds to perfectly elastic collision and to yields to a negative n_{COR} value when R is very small, which corresponds to the case of a perfectly plastic collision. Both situations are in accordance to the principals described in impact mechanics.

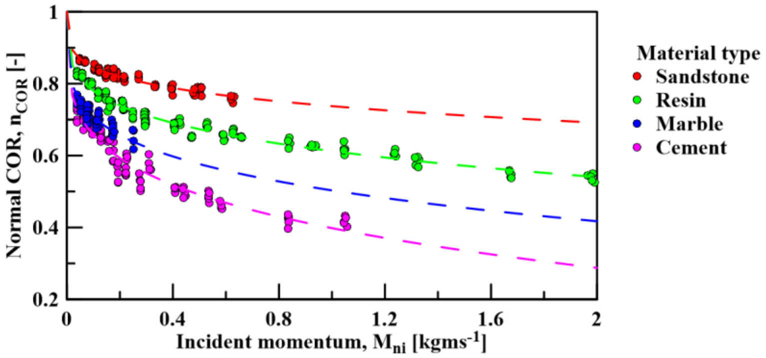

Figure 1. Normal COR as a function of incident momentum from the first testing stage

In the second testing stage, further tests were conducted by letting the spheres impact on a surface of a different material. It was seen that n_{COR} is affected by the material type of the impact surface, since n_{COR} was found to be increased as the surface became harder. This effect is quantified by calculating n_{COR} from Eq.1 with the Schmidt hardness of the block (R_b) and by introducing the correction factor c_{rh} defined as:

$$c_{rh}=2R_b/(R_s+R_b) \qquad (2)$$

Where R_s is the Schmidt hardness of the impact surface. Eq. 2 yields to one when R_s equals R_b, which corresponds to the test conditions applied in the first testing stage.

In the third testing stage the effects of impact angle and angular velocity were examined by conducting inclined impact tests. The sandstone, marble and cement materials were used along with all block sizes, achieving velocity magnitudes in the range from 1.9 to 6.6ms^{-1}, impact angles from 20 to 65°, and angular velocities between 100 and 400s^{-1}.

The results verified the previous findings (i.e. n_{COR} decreases with the intensity of the impact and increases as the materials become harder) and that n_{COR} decreases as the impact angle tends to 90°, which has been noted in many relevant studies. However, the angular velocity did not have any effect on n_{COR}. Also, these results verified that the semi-empirical model that was extrapolated form the previous testing stages is applicable for inclined impacts as well, given that the normal component of the incident momentum is used. The relative error in the estimation of n_{COR} for oblique impacts using Eq. 3 is limited to ±15%, which is significantly lower compared to what found in relevant literature. On its final form, the semi-empirical model for the estimation of n_{COR} is:

$$n_{COR} = c_{rh}\,[(0.027R_b\text{-}1.536)M_{ni}^{0.244} + 1] \qquad (3)$$

None of the investigated parameters posed any measureable effect on t_{COR}. This is in line with the findings in relevant literature. Thus, t_{COR} is assumed to be primarily affected by the roughness of the impact surface in combination with the block shape, which form the contact geometry. This justifies the limited scatter in t_{COR} values in this study, since all tests were performed with spherical blocks impacting on planar surfaces, leading to repeatable impact configuration between tests.

Acknowledgements

This post-doctoral research was carried out with a scholarship granted by the State Scholarships Foundation of Greece (IKY) under the act “Supporting Post-Doctoral Researchers” of the Operational Program “Human Resources Development, Education and Life Lifelong Learning” (Thematic Priority Axes 6, 8, 9) and is co-funded by the European Social Fund (ESF) and the Greek Government.

References

Asteriou, P. Tsiambaos G., 2018. Effect of impact velocity, block mass and hardness on the coefficients of restitution for rockfall analysis. Int J Rock Mech Min Sci, 106, 41-50

Labiouse, V., Heidenreich, B., 2009. Half-scale experimental study of rockfall impacts on sandy slopes. Nat Hazards Earth Syst Sci, 9(6): 1981–1993.

Asteriou, P., Tsiambaos G., 2016. Empirical model for predicting rockfall trajectory direction. Rock Mech Rock Eng, 49(3): 927–941.

Asteriou, P., 2018. Effect of impact angle and rotational motion on the coefficients of restitution for rockfalls. Geotec Geol Eng.

Asteriou, P., Saroglou, H., Tsiambaos, G., 2012. Geotechnical and kinematic parameters affecting the coefficients of restitution for rock fall analysis. Int J Rock Mech Min Sci, 54. 103–113