ROCKFALLS: IN SITU TEST, KINEMATIC SIMULATION AND MITIGATION MEASURES – SASSO FARINACCIO CASE STUDY

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This research deals with the analysis of rockfall motion and the importance of kinematic simulations as well as in situ tests in designing of protection measures.
The study area is a talus slope located in Northern Italy (Provence of Sondrio), where rockfalls frequently occur. The positions and dimensions of fallen blocks were measured and used in the calibration process, performed through the back-analysis approach. The calibrated values of restitution coefficients were compared with those obtained from in situ tests, which were carried out on the examined slope. Looking at the resulting rock fall hazard, the bi-dimensional kinematic simulations were performed in order to individuate the most suitable location and dimensions of mitigation measures.

Keywords: rock falls, calibration process, mitigation measures, restitution coefficients.

INTRODUCTION

Rockfalls constitute a significant hazard in mountain areas or villages with abrupt topography, where it is not usually economically feasible to stabilise all the areas that may be sources of rockfalls [1]. Hence, the passive mitigation measures are widely diffuse in alpine areas subjected to rockfalls. The choice of the most effective location and mitigation design measures requires the analysis of possible block trajectories, by using kinematic mathematical models [2]. The fall path that a single block follows during in situ test, it was also proved that, for slopes with a fairly simple geometry, it is possible to obtain reasonable statistical distributions of rock trajectory endpoints [3], [4]. Actually, the kinematic simulations, furnish the expected values of kinetic energies, bounce height and travel distance of blocks prone to failure, computed using a statistically significant number of falling blocks. Of course, the simulations are a useful tool in any rock fall engineering planning, but they are reliable only if adequately calibrated, with the specific site location features [5].
This note reports an example of case study, which staring from an historical rock fall event define the possible future rock fall scenarios, which, using the simulations, are the basis of mitigation measures planning.

GEOLOGICAL CONTEXT

The area of study is a talus slope ($0.13km^2$ 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. Regarding the geological-structural context, this area pertains to the superior Austro-Alpine domain and is characterized by a thrust system, overlapping 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.

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IN SITU OBSERVATIONS

The last rockfall event occurred in the study area in autumn 2010. Numerous blocks detached from the steep cliff located on the top of talus cone. Some blocks stopped near the bottom of the cliff, where a terrace was built some years ago to capture falling blocks. With the time, the fallen debris and blocks piled, reducing the terrace effectiveness, and during the 2010 event, some blocks were able to overpass the terrace and reach the road and the Roasco River (one block). The locations of accessible fallen blocks were mapped (Figure 1), noting their dimensions. No fresh blocks, stopped along the talus slope, were recognizable.

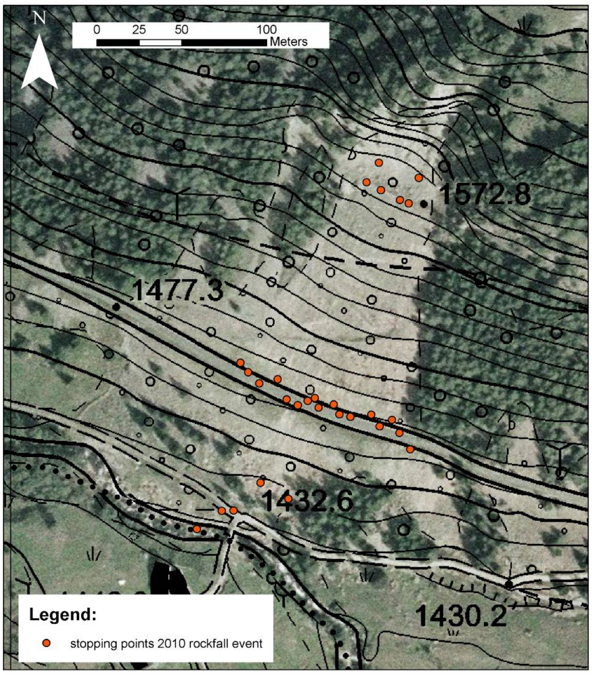


Figure 1 – Stopping locations of blocks fallen in autumn 2010

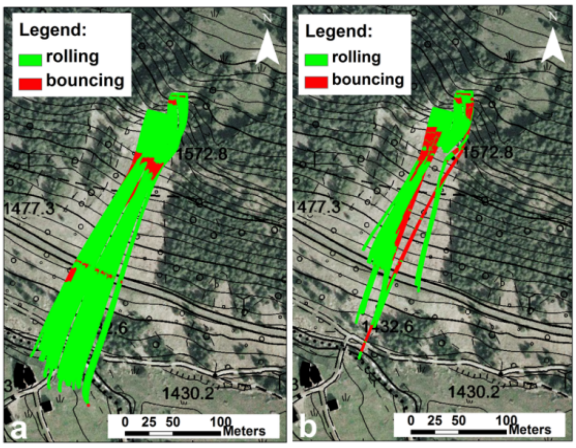
A detailed geomechanical survey was carried out on the cliff, according to the suggested methods for the quantitative description of discontinuities in rock masses [6]. One main sub-horizontal discontinuity set, related to the gneissic orientation of minerals, was individuated, together with three less persistent secondary sets. The orientations, accompanied by joint set spacing, give an average rock block volume of 1.5m^3. This volume is comparable with the dimensions of blocks fallen in 2010, and is the expected volume of future. Hence, it was used in the kinematic simulation for the analysis of possible future scenarios.

The comparison among the orientations of discontinuity sets, cliff, and the friction angle, computed according to the Barton & Choubey equation [7], show two different detachment mechanisms [8]: the sliding of block prevails on the Western side of the cliff, while the rock toppling on the Eastern side [9].

KINEMATIC SIMULATIONS AND BACK-ANALYSIS

Kinematic simulations are useful to study the propagation of blocks along a slope, being able to estimate the 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 falling phase is modelled by the ballistic parabola physics law, while the rebound is commonly described using normal and tangential restitution coefficients, expressed by the ratio between the velocity after and before the impact, respectively normal and tangential to the slope. Roll and slide phases are mainly controlled by the friction angle between the falling rock and slope surface. Models that analyse rock block trajectories need to incorporate all these kind of motion. The models can be classified in lumped mass (i.e. the rock mass is concentrated in its centre of gravity) and rigorous models (block shape and volume are considered). In this study, both methods were tested, using respectively CRSP [10] and Rotomap [11]. Regarding the topographic base, the former considers the 2D slope profile and the latter the 3D grid. Whatever is the simulation approach chosen, a big influence on the results is given by the topography, more it is accurate, better the results are.

Since the detailed topographic base of study area was not available, but only the DEM with 10 metres resolution, Rotomap was initially employed to calibrate motion parameters, using a back-analysis approach. Initially, a set of coefficients was derived averaging out bibliographic values, obtained in similar geological and geomorphological contexts [2], [12], [13], [14]. At a later stage, these values were arranged until the best match with the stopping position of blocks, mapped for the 2010 rockfall event (Figure 1), was found (Figure 2).



	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

Figure 2 – Comparison between the 3D rock fall path obtained using the bibliographical values (a) and the back-calibrated parametres (b). The values of the used normal and tangential restitution coefficients (respectively Kn and Kt), the dynamic rolling friction coefficient (μ) and the roughness (ε) are reported on the table on the right.

When numerous kinds of outcropping materials are considered, infinite different combinations of motion coefficients 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 by comparing the results of the numerical simulation with those of in situ tests [9].

Camera	**Parameter**	**Estimated value**	**Measured value**
Upper camera	Mean velocity [m/s]	8.47	5.07
	Maximum velocity [m/s]	14.12	12.45
Lower camera	Mean velocity [m/s]	14.83	15.15
	Maximum velocity [m/s]	22.92	20.13

Table 1 – Comparison between the estimated and measured velocity values

Even if the interpretation of the in situ tests, give some unusually high restitution coefficients [14], the velocities near the camera, estimated through 1000 simulations with CRSP, fit very well with the measured velocities [Table 1]. On the contrary, the bounce heights are overestimated by simulations. The section used to perform the simulations with CRPS, was chosen in the centre of the talus slope, according to maximum slope angle. Since for the design of mitigation measures accurate results are necessary, with the aim improve them, some GPS points were measured along the chosen topographical section, and they were used to construct a more detailed slope profile.

MITIGATION MEASURES

The detailed analysis of the motion along the 2D profile indicate that the best position to put a rockfall net is at the top of talus slope, near the edge of the terrace. Actually, if a block overpasses the terrace, its probability to reach the road is equal to 1, due to the steepness of the talus slope and the absence of trees. Moreover, the estimated velocities and energies near the road are bigger than those near the terrace are. Near the terrace, the estimated mean kinetic energy is equal to 540 kJ, while near the road the mean value is equal to 1100 kJ. It follows that it is necessary to stop the blocks on the terrace, being a more delimited area than along the road. The best solution therefore will be a high energy rockfall fence on the edge of terrace and a low energy barrier fence along the road. This could be useful considering that after an impact the fence lost the 60% of its effectiveness and should be replaced.

CONCLUSIONS

In this note an example of rockfall case study was presented. The kinematic simulations gave an important support in the design of mitigation measures. The parameters describing the rock fall motion were calibrated, through a back-analysis process, using the stopping positions of blocks. Although the restitution coefficient measured in field, during in situ tests, are higher than those estimated by back-analysis, the estimated and measured velocities are comparable.

REFERENCES

[1] ALEJANO L.R., PONS B., BASTANTE F.G., ALSONSO E., STOCKHAUSEN H.W. (2007) Slope geometry design as a means for controlling rockfalls in quarries. International Journal of Rock Mechanics and Mining Sciences, 44: 903-921

[2] GIANI G.P., GIACOMINI A., MIGLIAZZA M., SEGALINI A. (2004) Experimental and theoretical studies to improve rockfall analysis and protection work design. Rock Mechanics and Rock Engineering, 37: 369-389

[3] RITCHIE A.M. (1963) The evaluation of rockfall and its control. Highway Research Record, 17: 13-28

[4] PIERSON L.A., GUILLIXSON C.F., CHASSIE R.G. (2001) Rockfall catchment area design guide. Final report SPR-3 (032)

[5] FERRARI F., GIANI G.P., APUANI T. (2012) Mount Farinaccio rockfall: comparison between kinematic simulations and experimental field tests. Rendiconti online della Società Geologica Italiana, 19: 40-41

[6] International Society for Rock Mechanics I.S.R.M. (1977) - Suggested methods for the quantitative description of discontinuities in rock masses. International Journal of Rock Mechanics and Mining Science and Geomechanical Abstract, 15 (6): 319-368

[7] BARTON N., CHOUBEY V. (1977) The Shear Strength of Rock Joints in Theory and Practice Rock Mechanics. Rock Mechanics 10 (1/2): 1-54

[8] MARKLAND J.T. (1972) A useful technique for estimating the stability of rock slopes when the rigid wedge sliding type of failure is expected. Imperial College Rock Mechanics Research Report, 19

[9] FERRARI F., GIANI G.P., APUANI T. (2013) Towards the comprehension of rockfall motion, with the aid of in situ tests. Italian Journal of Engineering Geology and Environment, 6: 163-171

[10] PFEIFFER T., BOWEN T. (1989) Computer simulation of rockfalls. Bulletin of the Association of Engineering Geologists, 26 (1): 135–146

[11] SCIOLDO G. (1991) Rotomap: analisi statistica del rotolamento dei massi. Guida informatica ambientale, Patron, 81-84

[12] PITEAU D.R., CLAYTON R. (1987) Computer rockfall model. Proceedings of Meeting on Rockfall Dynamics and Protective Works Effectiveness, 123-125

[13] AZZONI A., ROSSI P.P., DRIGO E., GIANI G.P., ZANINETTI A. (1992) In situ observation of rockfall analysis parameters. Proceedings of 6th International Symposium on Landslides, 307-314

[14] FERRARI F., GIANI G.P., APUANI T. (2013) Why can rockfall normal restitution coefficient be higher than one? Rendiconti online della Società Geologica Italiana, 24: 122-124