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In situ observation of rockfall analysis parameters

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ABSTRACT: Rockfall analysis has been the subject of several research programs carried out in the last years. However, even if the rockfall problem has a great significance with respect to safety and cost considerations, there are no many experimental data available on rockfall motion.
This paper presents the results of experimental work carried out through in situ rockfall tests. The tests were performed by throwing blocks and monitoring their falls by several video cameras. The data, recorded on a graphic computer, were then interpreted with a rockfall analytical model, by determining the equation of motion parameters of each type of movement. Different rock slope sites were investigated in order to analyze the influence of the block size, shape and mechanical features and the influence of the nature of the ground and its geometry. Specifically, the investigation dealt with: the coefficients of restitution of the ground slope during the block bouncing, the rolling friction coefficients, the prevailing type of block movement and the kinetic energy assumed by the block during the movement.
The rockfall parameters gathered, cover a wide range of real cases providing useful input data for the application of analysis and design methods to aid in the engineering solution of rockfall problems.

1 INTRODUCTION

Rockfall analysis is carried out in potentially unstable slopes where the danger of block detachment and fall is imminent. The aim of the analysis is to predict the path and the kinetic energy of the block during its travel.

The principal kinds of motion of a falling block are: free falling, bouncing, rolling and sliding. They depend on the mechanical and geometrical features of the block and of the slope and can occur alone or, more frequently, combined, such as the cases of rolling with sliding or rolling with bouncing.

The analytical description of the block motion is usually carried out through a numerical model by considering only the prevailing movement and neglecting the secondary one.

The type of motion in the model depends on the geometrical and geomechanical characteristics of both the slope and the block, as well as on the mechanical parameters used to describe the slope-block interaction.

The rockfall parameters governing the block motion are the coefficients of restitution for bouncing and the friction coefficients for rolling and sliding.

The rockfall model can take into account different phenomena occurring during block travel. Two main kinds of models can generally be used depending on whether the hypotesis is that the block is a point mass or a solid with a defined geometry.

In simplified rockfall models the block motion is represented by the motion of a point which falls and bounces over the slope. The phenomena of the impact and of bouncing are only driven by the coefficients of restitution, which represent the ratio between the energy before and after the impact, computed on the basis of the translational velocity.

In more complex models the block is schematized as a "solid" of known geometry, such as an ellipsoidal shape. In this case, the rotation in the air before and after impact is also considered. The block motion is so described by considering a restitution coefficient able to take into account both translational and rotational variations of the velocities.

Rockfall parameters are usually determined on the basis of the geological features of the slope. Compact rock slopes have higher coefficients of restitution than debris or earth slopes.

The values for rockfall parameters, stated in the literature, are extremely variable for the different types of bedrock, debris or soil. The dynamic phenomena of the impact can be rigorously studied by examining the following parameters: the shape, the weight and the size of a block, as well as the strength, the geometry, the roughness and the deformation features of the slope. Small variations in the block and slope features can however result in large variations in the values of the coefficients of restitution and, as a consequence, in the type of block motion.

The influence of block and slope parameters on rockfall has been investigated in this research by observing block falls along slopes in different sites.

Different types of quarry rock faces, debris and natural slopes have been examined in regard to different shapes, sizes and lithologies of the blocks.

The analytical interpretation of the video recordings of the rockfalls allowed the authors to estimate some rockfall parameters and their spatial variability.

2 IN SITU OBSERVATIONS OF ROCKFALL

2.1 Study sites

Between 1989 and 1991 several experiments were carried out on slopes of different geological and geomorphological features. All the experiments were aimed at understanding the different types of motion of single rocks, which were characterized by various strengths, shapes and sizes.

The tests have been carried out in the following sites:

- the quartzite quarry area near Strozza (Bergamo);
- a gneiss quarry in the Luserna area (Torino);
- an ortogneiss quarry in Iselle (Domodossola - Novara);
- an abandoned limestone quarry in Cagliari;
- a natural slope in Val Malenco (Sondrio).

In the Strozza area the rockfall tests have been carried out on two different slopes. The first was composed of a subvertical rock face 25 metres high and a lower thin talus slope 40 metres long and 30 degrees of inclination. The second slope, 70 metres long and inclined 40 degrees, was characterized by uniform detrital material mixed with small boulders.

The quartzite blocks thrown down the slopes were mainly of prismatic shape, to a lesser extent spheroidal, while the volumes ranged between 0.5 m^3 and 3.0 m^3.

The examined slope in the quarry area of Luserna was composed of a natural subvertical rock scarp, 70 metres high, with a lower talus slope about 700 metres long and an average inclination of 30 degrees, characterized by detrital material mixed with small boulders. The launched gneiss blocks ("Luserna stone") had mainly a tabular shape, to a lesser extent prismatic. The volumes of the rocks ranged between 0.5 m^3 and 2.0 m^3.

The slope of the Iselle quarry is about 200 metres long, with an average inclination of 35-40 degrees with local benches 5-6 metres wide. The upper part of the slope (first 50 metres) is composed of bedrock material, while the lower part is composed of very large rock boulders (of some cubic metres), which give to the slope its roughness. The chosen test blocks were composed of ortogneiss ("Serizzo") with a prismatic and to a lesser extent tabular shape. The volumes ranged from about 0.5 m^3 to 3.0 m^3.

The tested slope of the Cagliari quarry area is about 60 metres long with an average inclination of 25-30 degrees. Two main travelling lines were observed on this slope.

The examined slope in Val Malenco is a deep chute about 1700 metres long, 20 metres wide and with a mean inclination of about 40 degrees. It is characterized by three different parts: the upper part of the slope (200 metres) is rocky and inclined about 55 degrees, the central tract (about 650 metres long with a dip of 40 degrees) is mainly characterized by thin detrital material with large rock boulders, the lower part is less steep and characterized by talus with vegetation.

2.2 Description of field experiments

Three or more video-cameras were placed along each test slope at different lateral positions depending upon the length of the slope and the morphological condition of the site. The positioning of the cameras was constrained by the necessity of obtaining a good lateral view of the rock fall, as much as possible perpendicular to the plane containing the predicted trajectory. A movie-camera was also placed in a frontal position, in order to evaluate the lateral dispersion of the falling block from the ideal plane containing its trajectory.

The cameras operated at a speed of 25 shots/s, recording the rock motion at various stages, especially during the impact phases. In most cases the recording of the final stage of the rockfall permitted the evaluation of the mean run-out distances.

The main types of motion observed at the different test sites were the following:

- free falling with impact on rock (Luserna);
- bouncing (Strozza first slope, Iselle, Val Malenco);

- rolling (Strozza first and second slope, Cagliari, Iselle);
- combined rolling and bouncing (Cagliari, Strozza, Iselle).

The video registrations were analysed in the laboratory, utilizing a software set up to compute the barycentre co-ordinates for each examined position of the block during the motion. The scale of the system was obtained by comparing the recorded images with topographical references installed and surveyed along the slope.

The two components (v_x and v_y) of the block translational velocity during the different stages of the motion (before and after impacts) have been calculated by knowing the time interval occurring between each shot (4 hundredths of a second). The two components were then transformed into the tangential and normal components to the slope. When a complete revolution of the block was clearly recognizable, the rotational velocity was also computed.

3 ANALYSIS OF THE RECORDS

The tests were analysed by determining the block velocity along the fall trajectory; in the case of longer or complex slopes only the most significant part of the fall was considered.

Velocity - distance (v - d) diagrams have been obtained for all the examined sites. Velocities were assessed at variable time intervals depending on the image and recording system features. Therefore the block motion was not computed continuously. It is possible to recognize through the v - d diagrams the principal types of the block motion: free falls, impacts, bounces and rolling with multiple collisions.

The free fall motion is only governed by the acceleration of gravity as air resistance is negligible. This type of motion is therefore characterized in the v - d diagrams by a regular velocity increase. The inclination angle of the block motion curves is constant for each free falling phase between two successive bounces.

The impacts are easily recognizable by the sharp decreases of velocities in the v - d diagrams.

The rolling motion velocity is governed by the rolling friction parameters and is characterized by a linear path of velocity in the v - d diagram. Rolling with multiple collisions is produced by the combination of rolling and bouncing and is recognizable by a typical stepped diagram.

Some of the most significant recorded block motions are shown here. Figure 1a represents three relevant block bounces preceded by free fall and impact mixed with rolling and bouncing. The diagram represents the observations carried out at the Iselle site.

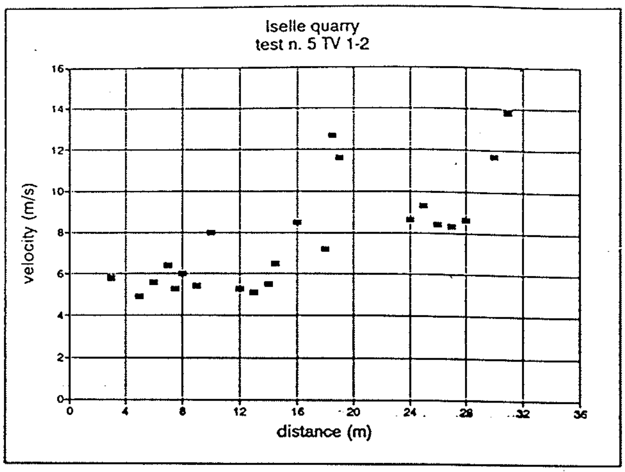

Figure 1a

The motion of three blocks along the central part of the Val Malenco slope is reported in figure 1b. The motion of the blocks is characterized by bounces intermixed with rollings; one of the blocks was stopped by the impact against a large boulder.

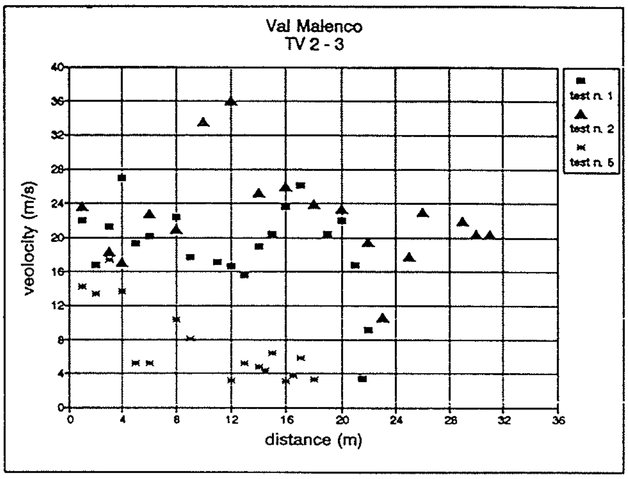

Figure 1b

The velocity of a block travelling on a slope varies according to the slope topography and the shape and size of the block.

Six v - d diagrams are plotted in figures 2a and 2b. Figure 2a refers to the rolling with multiple collisions of a spheroidal shape block during the first part of its travel along the Cagliari quarry slope. Figure 2b represents the rolling with multiple collisions of prismatic shape blocks during the last part of their travel on the Strozza first slope.

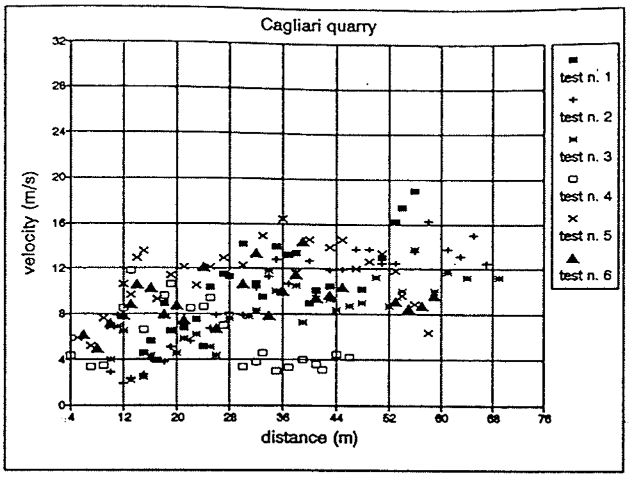

Figure 2a

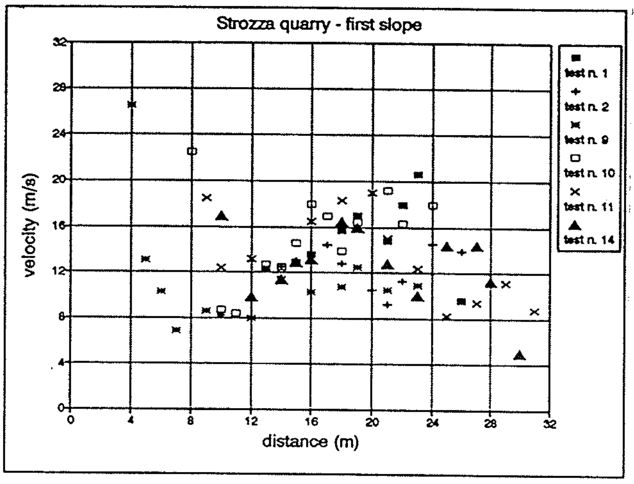

Figure 2b

The block motion along the two slopes is similar, even though the causes of the multiple collisions at the two sites are different. At the Cagliari site, where the rock is softer and block asperities tend to be smoothed out during the falls, bouncing is mainly caused by the slope roughness. At the Strozza site on the other hand, the multiple collisions are mainly caused by the block asperities. In this case, in fact, the quartzite blocks are very hard and maintain their initial integrity throughout the travelled paths.

During the elaboration of the recorded tests some other observations have been made.

- Blocks of similar shape and size thrown down from the same point on a slope almost always have similar trajectories and arrival zones, even though their computed velocities progressively differ from each other with the distance from the source.
- In tabular and to a lesser extent prismatic blocks, the motion tends to become similar to the rolling of a wheel, with the maximum inertia axes lying in the plane of the block motion. This movement condition is the most dangerous since it corresponds to the minimum energy dissipation during the travel.
- In debris slopes, when the average size of the falling blocks is a certain degree larger than the average debris size, rolling prevails and the block collisions do not vary the velocities in a significant way (Strozza second slope).

The trajectories of approximately twenty blocks on the Strozza site have been analysed by determining the mean block velocity and standard deviation, at different distances from the beginning of the motion (figure 3).

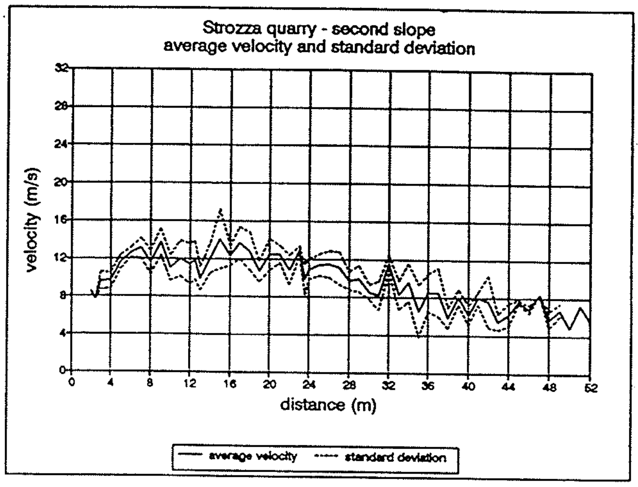

Figure 3

The analysis of the rockfalls has been done considering the block as point mass, mainly because of the difficulties in gathering the data necessary for the application of more complex models in all the examined falls.

The models which consider the block as a point mass are able to determine the passage between a bouncing and a rolling phase by considering the block energy and the principle of maximum motion efficiency. This principle was applied by Hungr & Evans (1988), who introduced, to characterize the block motion, a quantity called "height of the block energy", E. During the fall E is equal to $z + v^2 / 2g$, where z is the block elevation above a reference level, g is the acceleration of gravity and v is the magnitude of the resultant block velocity. A diagram of "energy height" versus distance is characterized, for the case of a block bouncing on a slope, by a series of steps separated by horizontal lines (energy lines). The length of each line is the path of the block in the air between two successive rebounds.. The difference in height of each energy line segment in the E - d diagram represents the energy loss during the impact. In a rolling phase, the E - d diagram is characterized by a linear decrease of the energy height. The coefficients of restitution can be

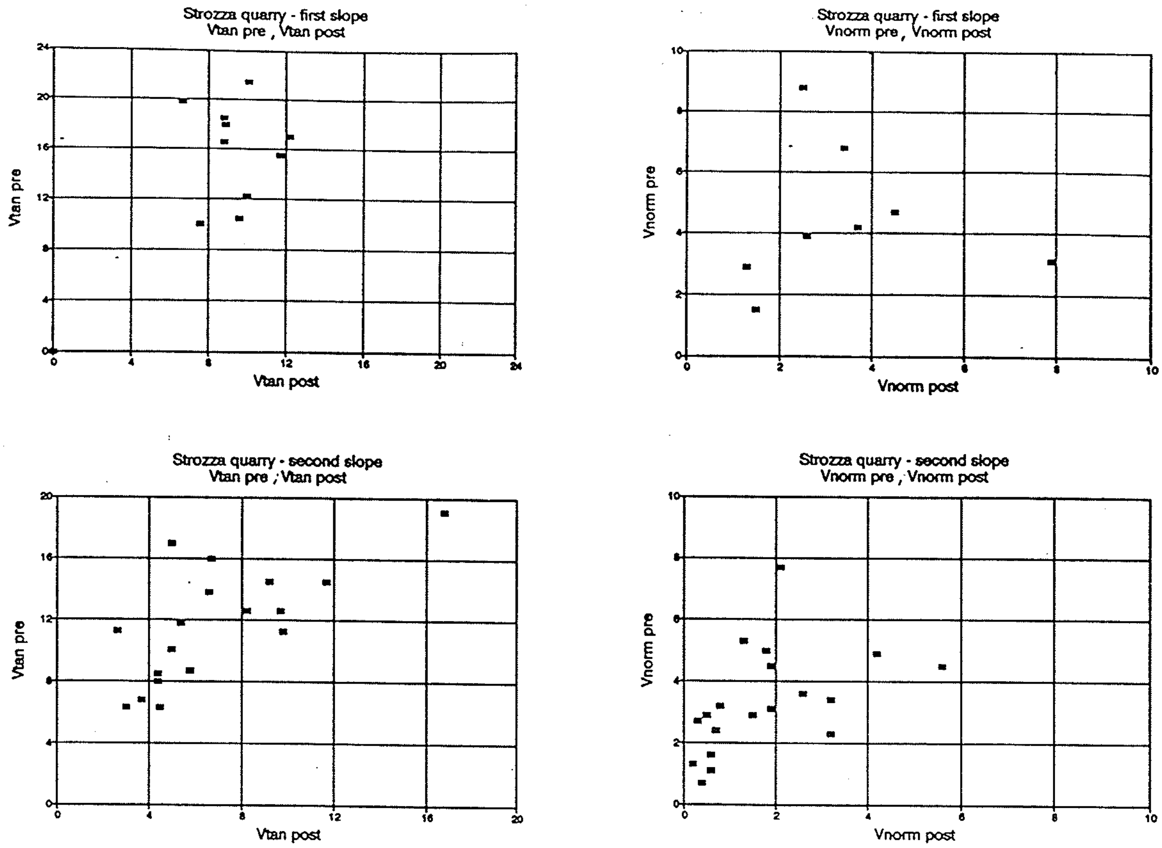

Figure 5a

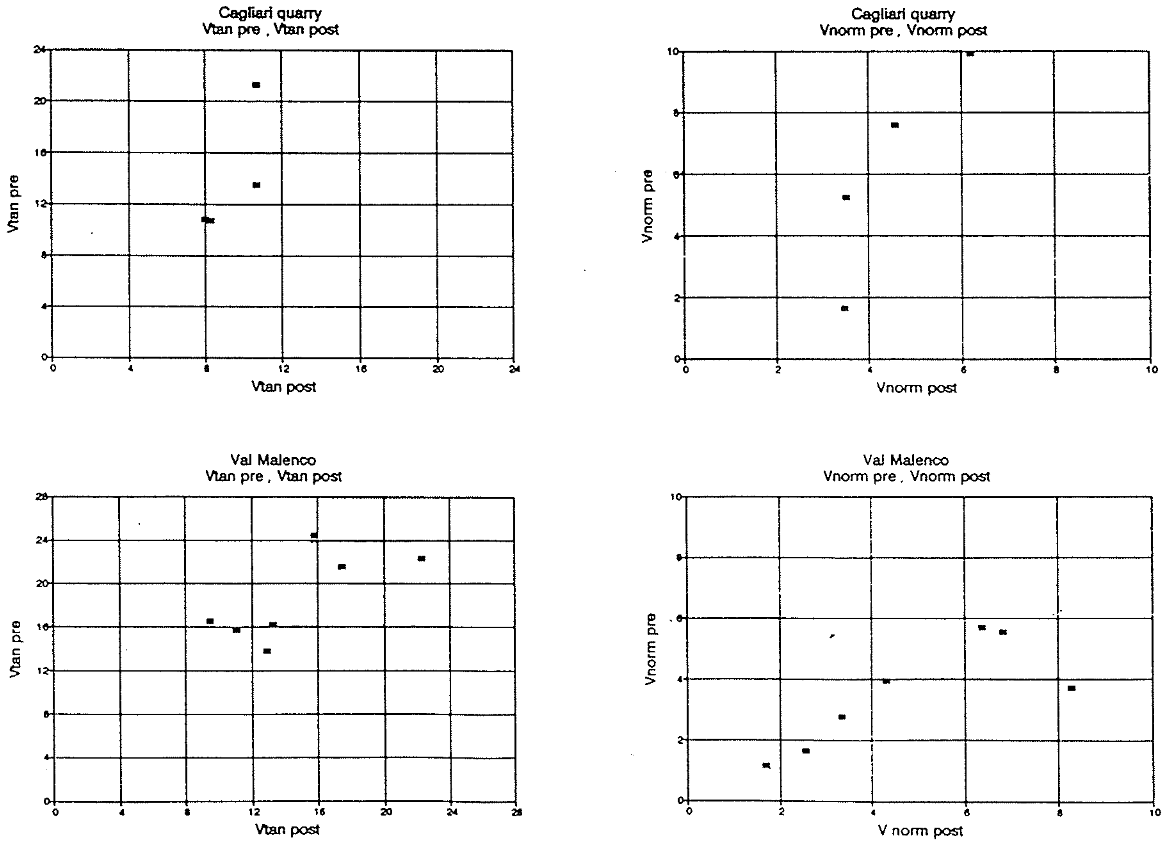

Figure 5b

correlated to the energy loss during an impact by using the following formula:

$$\Delta E = \frac{v^2}{2g}\left[\left(\frac{K_t^2 + K_{n2}\tan^2\alpha}{1 + \tan^2\alpha}\right) - 1\right] \quad (1)$$

were α is the angle of incidence prior to the impact, and Kn and Kt are the normal and tangential coefficients of restitution, respectively.

According to Hungr & Evans, the transition from bouncing to rolling is conditioned by the rolling friction coefficient, a parameter related to the dissipation of energy which is given by the inclination of the energy line during the rolling motion. Considering the principle of the maximum efficiency of motion (which allows to determine whether the rolling or the bouncing phase corresponds to the lowest energy dissipation), rolling constitutes the most efficient motion when:
$\Delta E/\Delta l > \mu$, where Δl is the distance between two successive rebounds and μ is the rolling friction coefficient computed in the diagram.

Figures 4a and 4b show the corresponding E - d diagrams for two rockfalls on the Strozza and Val Malenco slopes.

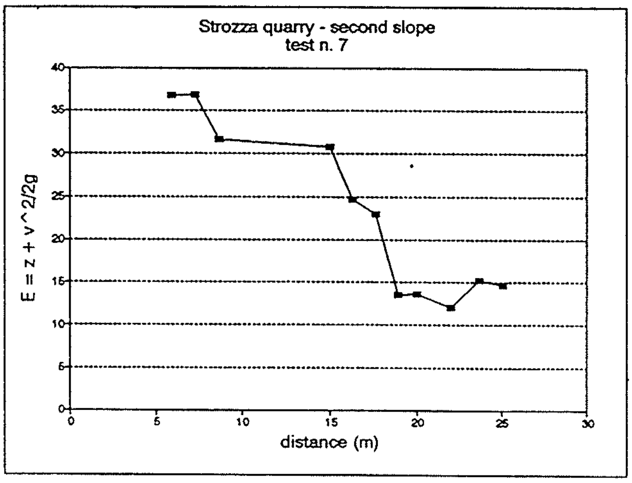

Figure 4a

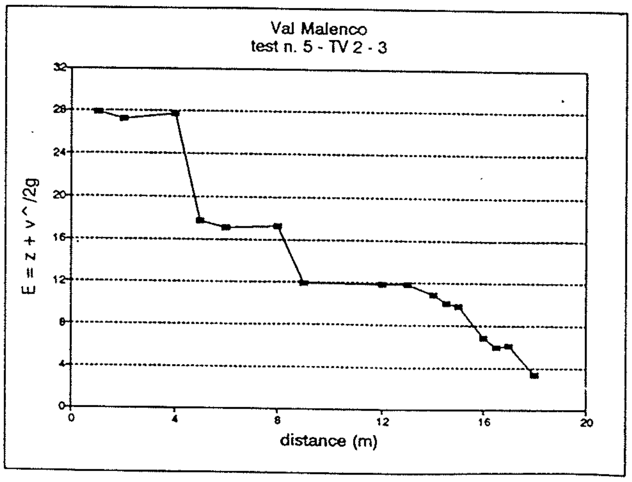

Figure 4b

The "energy line" method allows one to obtain more reliable pre and post - impact velocity values than those obtained by graphical elaboration in the instants preceding and following the falls since it utilizes the values gathered by several video shots. The "energy line" method was also used to determine the coefficients of restitution and of rolling friction.

4 DISCUSSION AND CONCLUSIONS

The rockfall is generally constituted by four principal kinds of motion - free falling, sliding, bouncing and rolling, which can occur alone or, more frequently, combined with each other.

The single motions are quite easy to model because of their dynamic characteristics, which permit good predictions about trajectories and energies involved.

This research has been mainly aimed toward the composed rolling and bouncing motion (rolling with multiple collisions), which is the most complex motion from the dynamic point of view and probably the most important in terms of geological risks.

This motion generally occurs since rolling blocks are not perfectly rounded and slopes are rough. This movement condition can be the most efficient not only for spheroidal blocks but also for tabular and prismatic ones, if their velocity is high enough to allow them to rotate along the minimum inertia axis with the movement occurring in the plane of the block's maximum cross section (as seen in the Luserna tests). It is characterized by trajectories very difficult to foresee and allows the block to gather very high energy with quite low possibility of breakage or consistent loss of energy during the impact. Furthermore it typically occurs on the lower parts of the slope, which are generally smoother and closer to civil structures.

Figures 5a and 5b report for the Strozza, Cagliari and Val Malenco slopes the diagrams of tangential and normal velocities measured before and after collisions and impacts.

The ratios between the post and pre - impact tangential and normal velocities give the tangential and normal coefficients of restitution respectively. Greater values of the coefficient of restitution represent smaller decreases in velocity usually caused by multiple collisions during a rolling movement. Lower values of the coefficient correspond to greater velocity reduction and are usually typical of a bouncing motion.

As far as the coefficients of restitution are concerned, it is possible to observe the following:

- the medium - high values of the coefficients for the rolling and bouncing motion in the Cagliari test are due to the smoothness of the slope.
- In the Val Malenco, because of the hardness of the slope, the coefficients of restitution are high even though the prevailing movement is a bouncing. The coefficients of restitution have been evaluated in cases in which the tangential velocities are on the average four times greater than the normal velocities. In this velocity field the rotational moments generated by the impacts provoke a relative increase of the post-impact normal velocity and a decrease of the post-impact tangential velocity.
- In the Strozza first slope it is possible to observe velocities related both to bouncing and to rolling with multiple collisions. Due to the energy dissipation during the impacts, the coefficients in bouncing motion are quite low. In the rolling and bouncing motion, tangential velocities are reduced by collisions and the rotational moments occurring at the block-slope contacts determine the relative increase of normal velocity.
- In the Strozza second slope, the low values during the rolling and bouncing motion are mainly due to the softness of the debris slope.

Table 1 reports the main characteristics of the tests, and in particular the average values determined for the coefficients of restitution and for the rolling friction coefficients computed according to Hungr & Evans.

The work is continuing at present.

Table 1

Site	Height * (m)	Length ** (m)	Inclination ***	Geology of the slope	K_t	K_n	μ_r
Strozza 1th	0	75	80 rock face 30 lower talus	rock / thin debris	0.45 bouncing 0.75 rolling and bouncing	0.45bouncing 0.85 rolling and bouncing	0.97±0.184
Strozza 2th	0	70	40	fine debris	0.66	0.30	0.75±0.159
Cagliari	0	60	25	debris and earth	0.66	0.62	0.39±0.117
Val Malenco	400	60	40	coarse debris	0.80	1.22	0.88±0.240
Luserna	0	70	80	rock			1.31±0.163
Iselle	10	60	40	coarse debris			0.84±0.301

* difference in elevation between the source and the monitored slope
** length of the monitored slope
*** inclination of the monitored slope

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