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Experimental and Theoretical Studies to Improve Rock Fall Analysis and Protection Work Design

By

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Summary

This paper reports an analysis procedure for the evaluation of the features of the motion of blocks detaching from a steep rock wall and traveling down the slope below. Starting from the execution of real scale rock fall tests, carried out on two slopes having different morphology and lithology, the paper describes the methodology used for test interpretation and a procedure for the evaluation of the parameters best suited to the description of rock fall motion. The influence of the parameters assessed on the prediction of the rock fall trajectory was also investigated using two-dimensional and three-dimensional numerical models. These models were calibrated by means of a back analysis of the in situ tests, which also allowed the evaluation of the uncertainties involved in the parameters experimentally estimated.

Keywords: Rock fall analysis, in situ tests, experimental data, computational model.

Introduction

In order to choose and design rock fall protection systems, it is necessary to observe and analyze a rock block detaching from a steep slope and traveling down the slope. Although there are many scientific papers regarding the morphological and lithological features of rock fall prone areas, objective indications for the evaluation of the parameters governing rock fall motion and a methodology for international standardization of in situ tests are still incomplete.

Up to the beginning of the 1960s (Ritchie, 1963), rock fall motion was represented as a series of aerial trajectories and rebounds. Various authors (Wu, 1985; Hungr and Evans, 1988; Evans and Hungr, 1993; Piteau and Clayton, 1976) developed field experiments in order to gather in situ parameters describing the impact phenomenon.

A further in-depth description of the phenomenon involved the introduction of a block movement characterized by aerial rotation and multiple soil collisions. For this purpose the phenomenon was described by taking into account block geometry and evaluating the rotational moment generated by the collisions. In this category are the works of Bozzolo and Pamini (1986), Azzoni et al. (1995), and experimental works aimed at recovering the equivalent rolling coefficient (Pfeiffer and Bowen, 1989).

Further in-depth studies, carried out in order to take into better account the three-dimensional nature of the phenomena, developed in both analytical and numerical form, can be ascribed to Descoudres and Zimmermann (1987), and Scioldo (1991), while the experimental aspects were studied by Azzoni and De Freitas (1995), and Giani (1992).

The application of either distinct element numerical models (PFC, 1999) or discontinuous deformation analysis models (DDA) (Shi, 1989) was proposed in order to represent the rock fall phenomenon as the mechanical behavior of a system of blocks. However, lack of experimental data supporting such models often prevents their effective use.

Finally, a few studies regarding the fragmentation of blocks along their path (Giani and Migliazza, 1999) have been carried out from both an experimental and a theoretical point of view, but they are still in their early stages.

This paper is concerned with both parameter definition and choice of methodology for the mathematical description of rock fall. It deals primarily with the execution and recording of in situ tests carried out on two slopes having different morphological and lithologic features, both subject to rock fall hazard.

Kinematic motion features were described from the recording of artificially produced rock falls. Subsequently parameters usually applied in two well-known calculation models were determined on the basis of the observed phenomena. Furthermore, the analytical methodologies were investigated in order to evaluate which of the models would be the most accurate. The in situ tests were designed to observe the following:

- triggering mechanisms of the rock fall;
- aerial phase of motion;
- impact with rotations and possible fragmentation of the blocks;
- velocity and kinetic energy;
- arrest.

In situ test methodologies, data acquisition, recording and processing are described in this paper along with characteristics of the test sites, and the interpretation and application of computational models for the description of the observed phenomena.

Test Methodology

Two series of real scale tests were carried out in order to find and estimate the characteristic parameters of the rock fall phenomenon. The first series of tests was carried out on a slope in the Apennines (Fig. 1), at a site located about 40 km south of Parma, Italy. The slope was characterized by a debris surface outcropping immediately below a natural ophiolitic cliff where rock falls originated. The second series of tests was performed on a slope in the Lepontine Alps (Northern Italy). The material

Fig. 1. Photograph of the Apennines field test slope

outcropping on the slope is debris dumped during the exploitation of the overhanging granite quarry (Fig. 2).

Prior to testing, a detailed topographic survey of both the slopes was carried out in order to define precisely the surface morphology and draw vertical sections (Figs. 3

Fig. 2. Photograph of the Alps field test slope

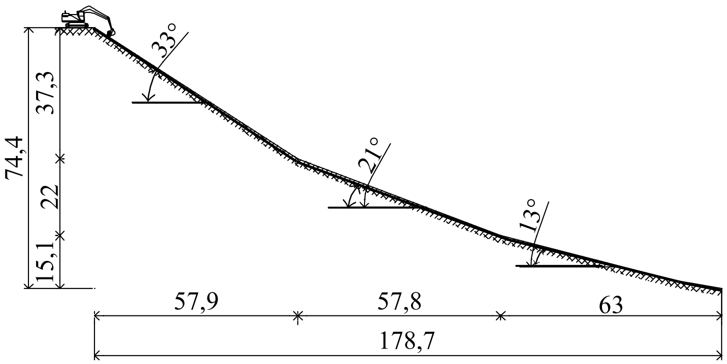

Fig. 3. Apennines slope section (dimensions in m)

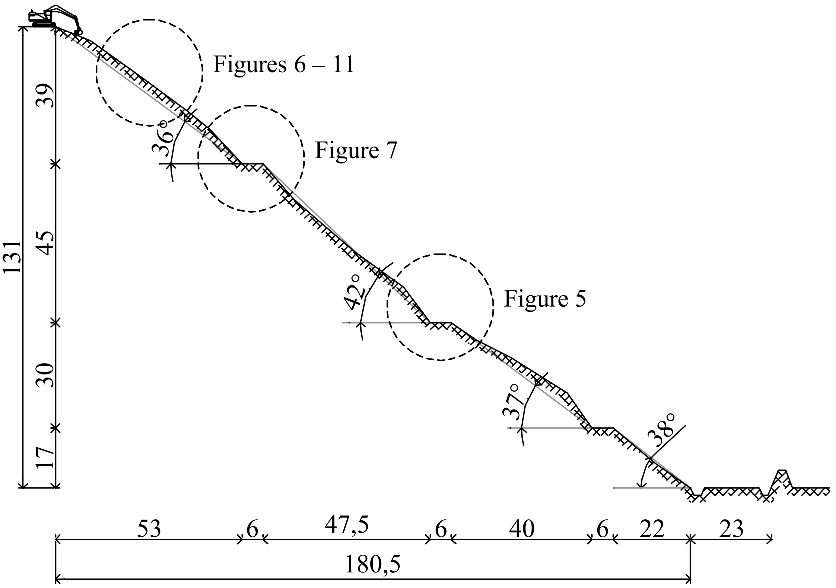

Fig. 4. Alpine slope section (dimensions in m)

and 4) relevant to the trajectories of the mobilized blocks. Once measured and catalogued according to their dimensions (volume) and shapes, the rock blocks were thrown from the top of both slopes using a mechanical excavator.

The tests were recorded by means of a series of fixed digital video cameras positioned along the path, in order to allow the analysis of each block's motion; positioned in this way the plane of the recorded image contains the trajectory of the blocks. Each camera's field has approximately the same width.

In the first series of tests (Apennines site), the morphology of the slope allowed the overlapping of adjacent video camera images, enabling spatial continuity of the recorded images. In the second series of tests (Alpine site) this was not possible. In the latter case, distinct sequences of images were obtained, as the video cameras were placed discontinuously along the slope.

The tests were planned so as to gather as many elements as possible for their subsequent interpretation by means of digital image processing. Therefore in the area covered by each video camera frame along the slope, ranging rods were positioned at known distances, in order to have useful metrical references during the digital image-processing phase. The recorded tapes were then transferred to a personal computer and subsequently edited to form the entire motion sequence of each block. In order to measure the velocity of the blocks, the filmed sequences were subdivided into single photograms, using a recording definition of 10 frames per second.

A specific program developed for digital image management allowed to obtain the geometrical parameters useful for the description of the motion, i.e. the position of the block centroid was referenced to a Cartesian system of coordinates associated with the video camera and the rotation angle of the block referred to a fixed reference direction.

Data Processing

The series of points determined from the image analysis allowed the definition of each block's trajectory. By knowing the coordinates of the block centroid and the time

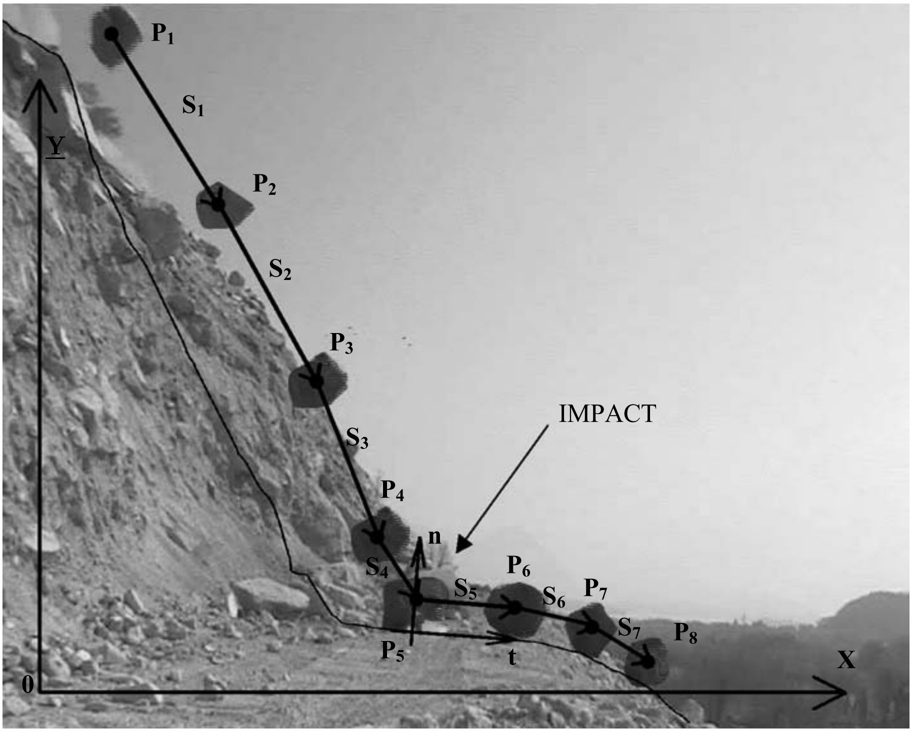

Fig. 5. Reconstruction of block position at different time intervals taken from the video camera recording and referred to the global (X, Y) and local (*n*, *t*) coordinate systems (Alpine site – see Fig. 4)

interval between two following frames, it was possible to calculate the kinematic parameters of the motion. Such quantities were referred to a couple of Cartesian coordinate systems: the first system (global) is the XY system (which is fixed for each video camera), where X is the horizontal axis and Y is the vertical axis; the second (local) is the n, t, system in which the direction n is the normal to the slope surface and t is the tangential. This reference system is defined by means of the section of the slope drawn from the detailed topographic survey.

By knowing the X and Y coordinates of the block centroid and the time interval between two following frames in chosen points along the trajectory, it was possible to calculate (Fig. 5, Alpine site):

- the displacement vector S (in terms of direction and magnitude) of the block centroid along the path and its components referred to both the global Cartesian system S_x and S_y, and the local Cartesian system S_n and S_t;
- the translation velocity vector V (in terms of direction and magnitude) of the block centroid along the path and its components referred to both the global Cartesian system V_x and V_y, and the local Cartesian system V_n and V_t;
- the energy head

$$h = z + \frac{v^2}{2g} \tag{1}$$

(where z is the height of the block along the path, v is the velocity of translation and g is the gravity acceleration).

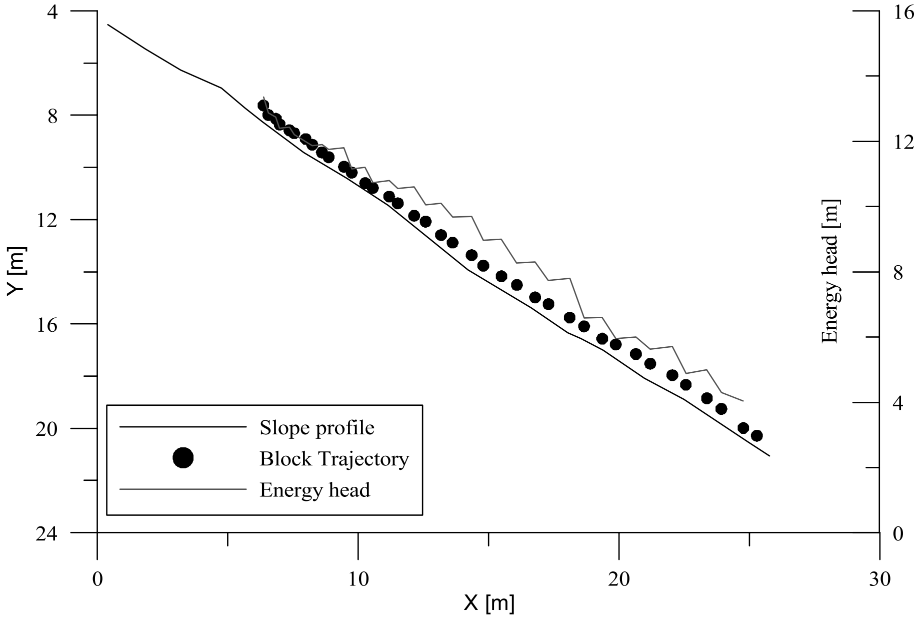

Fig. 6. Travel path and energy head diagram related to the equivalent rolling motion (Alpine site – see Fig. 4)

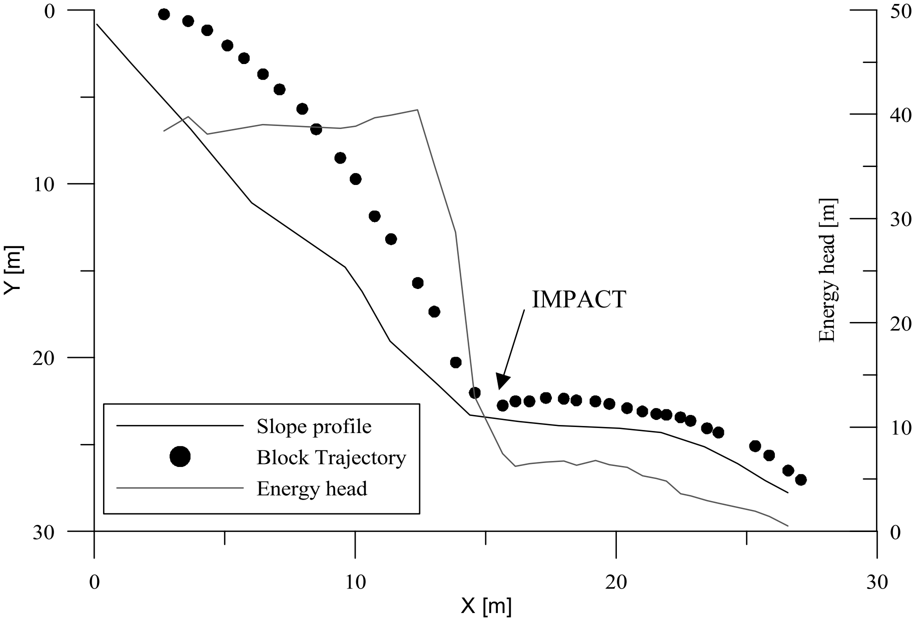

Fig. 7. Travel path and energy head diagram related to the aerial phase followed by an impact (Alpine site – see Fig. 4)

The results, reported in Figs. 6 and 7, show how the motion of the block characterized by short aerial rotations and frequent multiple collisions between the block and the slope surface, differs from the motion of the block characterized by infrequent impacts and long aerial phases.

Figure 6 (Alpine site) shows a motion characterized by short aerial rotations and frequent multiple collisions that is defined by a diagram h-L (height of energy versus traveled path) marked by sub-horizontal segments corresponding to the aerial rotation and sub-vertical segments related to the multiple collision motion phase which induces small losses of energy. This motion phase could be compared with an equivalent rolling motion.

In Fig. 7 (Alpine site) the aerial trajectory is characterized by a segment where the energy head is constant; the impact, instead, is recognizable as a concentrated energy loss. This motion is comparable with free falling and rebound.

Description of Field Tests

The Apennines site, chosen for real scale rock fall tests, is located in the Parma District, precisely in the high Manubiola valley, a right-hand tributary of the River Taro. The area is characterized by the presence of the Ophiolitic Complex of the middle Taro valley, comprising a "megabreccia" enclosing hectometric inclusions of serpentinite, serpentine breccias and polygenic breccias, often with predominant pelitic matrix (Fig. 1).

The tests (Giani et al., 2002) were carried out on a 180 m long portion of slope having an average inclination of 25/30°. The slope surface is covered by debris of variable size (with an average particle dimension of $30 \div 50$ cm, mingled with soil, sustaining low vegetation). During the test, 43 ophiolitic blocks with volumes varying from 0.01 to 0.6 m^3 were thrown down the slope. Figure 3 shows the slope section drawn along the average direction of the rock block traveling path. The slope is defined by three parts having different inclinations: 33° in the upper part, 21° in the middle part and 13° in the lower part.

The Alpine site is located on the left bank of the River Toce in a strip of territory delimited by the River Toce to the south and Lake Maggiore State Road n. 34 to the north. Located to the north of the State Road is a tailings pile formed of granitic rock debris (Fig. 2) coming from an exhausted quarry and currently subject to a second exploitation for feldspar production. The dump of granitic debris rests on a steep slope and has been terraced in order to enable exploitation of the quarry. The dump's rock slope is 130 m high with an average inclination of 36° (Fig. 4).

A rock fall protection embankment was built at the foot of the slope using rock blocks mixed with small-sized material, with height varying between 3–4 m in the eastern part and 6–8 m in the western part of the area. A part of level ground, approximately 25 m wide, was left between the embankment and the slope foot, for the loading of the material quarried. A ditch was excavated immediately adjacent to the embankment, on the uphill side, in order to reduce the energy of blocks that, once mobilized from the top of the slope, would eventually reach the embankment. The tests were carried out mobilizing 40 blocks having volumes varying from 0.1 to 4.5 m^3 from the top of the monitored slope. Such tests reproduce the worst situation in terms of length of trajectory and kinetic energy at this site.

Results

The analysis of the diagrams of energy heads acquired by each block thrown down the slope allowed to distinguish, for both sites examined, the type of motion characterized by impacts and rebounds from the type of motion characterized as equivalent rolling. Two coefficients of restitution were determined by examining processed data on impacts and bounces. The coefficients represent the kinetic energy dissipated during an impact phase.

A back analysis procedure was developed in order to interpret the rolling motion data and determine the equivalent rolling coefficients. These coefficients allowed us to quantify the loss of specific energy during the journey of each block down the slope.

Determination of Normal and Tangential Coefficients

The comparison between the block trajectory and the slope profile allowed to determine the correct impact positions. For each impact point, the components of the pre- and post-impact velocity vectors in the normal and tangential directions were determined (Fig. 8). The normal and tangential coefficients, for both sites, were

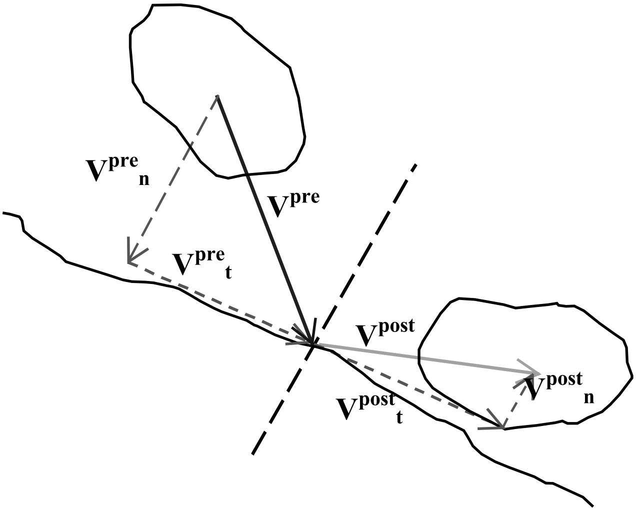

Fig. 8. Impact velocity scheme

Table 1. Values of the restitution coefficients calculated from the Apennine tests

Block number	k_n	k_t
16	0.52	0.77
17	0.62	0.75
19	0.47	0.80
20	0.34	0.81
43	0.47	0.84
Average values	0.48	0.79
Standard deviation	0.10	0.03

calculated as ratio between the post- and pre-impact values of the corresponding velocity components, as follows:

$$\text{Normal coefficient} \qquad k_n = \frac{V_n^{\text{post}}}{V_n^{\text{pre}}} \tag{2}$$

$$\text{Tangential coefficient} \qquad k_t = \frac{V_t^{\text{post}}}{V_t^{\text{pre}}} \tag{3}$$

Table 1 reports the values of k_n and k_t calculated from the experimental data obtained from the tests carried out in the Apennines. The data reported refer to single impacts of specific blocks. Since the motion is well characterized by an equivalent rolling movement, the data reported refer to significant bounces. The average values are obtained only by the reported data.

Table 2 shows the values of k_n and k_t coefficients obtained from each impact-rebound datum recorded during the test carried out on the Alpine site. The data refer to the restitution coefficients calculated during the traveling of single blocks. In some case the block motion arrested after one bounce only, in some other case the motion of

Table 2. Values of the restitution coefficients calculated from the Alpine tests

Block number	k_n	k_t
2	0.19	0.43
4	0.08	0.67
12	0.05	0.29
	0.05	0.41
15	0.12	0.41
	0.16	0.64
16	0.10	0.43
	0.07	0.43
	0.001	0.39
22	0.01	0.53
	0.69	0.36
25	0.23	0.36
	0.78	0.54
	0.58	0.53
	0.75	0.38
29	0.24	0.49
	0.05	0.48
	0.38	0.62
Average values	0.25	0.47
Standard deviation	0.26	0.10

the block stopped after two, three or four bounces. In the case of the Alpine site tests the movement is well characterized by a series of impacts and rebounds. The average and standard deviation values refer to all the reported data.

Estimate of Equivalent Rolling Coefficient

The equivalent rolling coefficient μ was estimated comparing the experimental curve showing the block tangential velocity along the path (parallel to the slope) and the correspondent theoretical curve obtained considering the ideal motion of a cylindrical block rolling along an inclined smooth plane.

The tangential velocity variation law, calculated along a plane with constant inclination α, displacement $(l - l_0)$, initial velocity v_0 and rolling coefficient μ can be expressed as:

$$v = \sqrt{v_0^2 - 2\mathrm{g} \cdot (l - l_0) \cdot (\sin\alpha - \mu\cos\alpha)}, \tag{4}$$

where g is the gravity acceleration.

For the interpretation of the tests carried out on the Apennines site, the slope was approximated by three segments with decreasing inclination (33°, 21° and 13°) and the theoretical curves were calculated either considering a single rolling coefficient for the whole slope or a different coefficient for each segment. Figure 9 reports the comparison between the experimental data and four theoretical curves, determined by considering a single rolling coefficient for the whole slope equal to, respectively, 0.3, 0.4, 0.5 e 0.6.

In Fig. 10 the theoretical curves are determined by using a rolling coefficient varying between 0.3 and 0.6 for the higher portion of the slope, while a constant

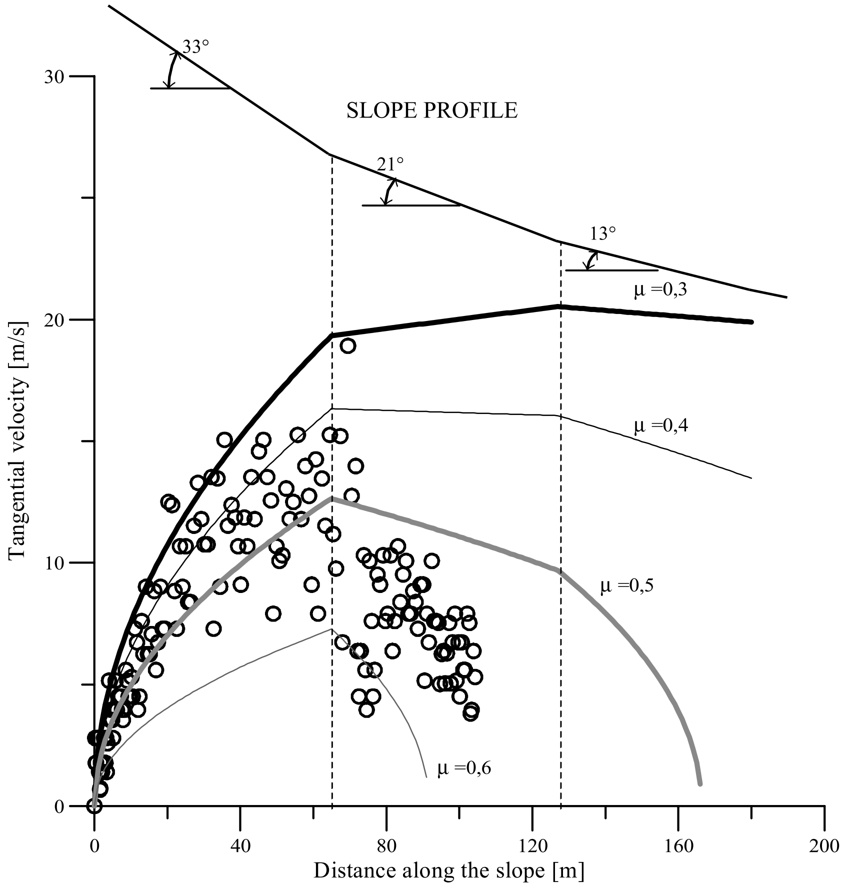

Fig. 9. Comparison between experimental (circles) and theoretical (lines) data for a mobilized block (Apennines site). Each theoretical curve is obtained using a constant rolling coefficient along the whole slope

rolling coefficient is applied (0.7) for the two lower portions. This is done in order to reach a better agreement with the experimental results obtained; in particular, in the higher portion of the slope the acceleration phase is well described, and so is the arrest phase in the lower one.

The experimental data show how the motion of a single block is characterized by frequent loss of energy corresponding to block-soil collisions, with an increase in velocity where slope inclination is higher than the rolling coefficient and a decrease in velocity where the rolling coefficient becomes greater than the slope inclination.

Figure 10 reports the comparison between the experimental data and the theoretical results obtained by considering a variation of μ along the slope. It can be seen that the best agreement between theoretical and experimental results is obtained considering a coefficient varying between 0.5 and 0.7 for the three segments.

In the test carried out on the Alpine site, the interpretation relates only to the initial phase of motion, which appeared to be well approximated as equivalent rolling.

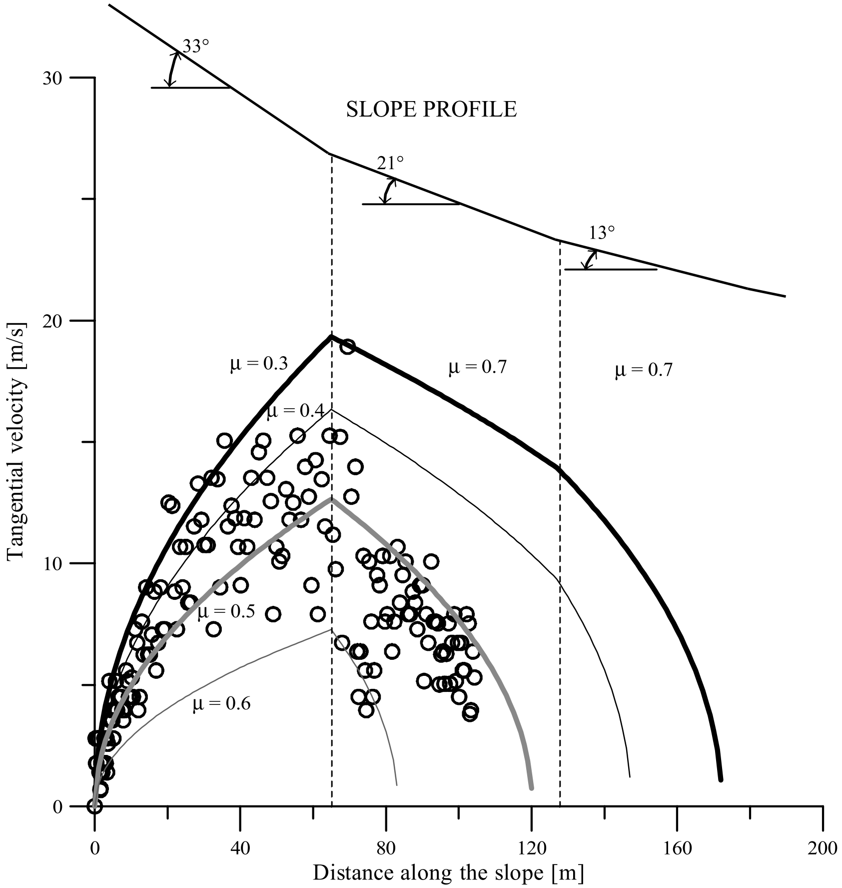

Fig. 10. Comparison between experimental (circles) and theoretical (lines) data for a mobilized block (Apennines site). Each theoretical curve is obtained using variable rolling coefficients for different portions of the slope

Figure 11 shows the comparison between experimental and theoretical curves for one of the blocks tested. The equivalent rolling coefficient that generates the best agreement between experimental and theoretical data, considered for all the blocks tested, is 0.53. The theoretical curve drawn in Fig. 11 is derived from Eq. (4) using that coefficient.

Predictive Models

The characteristic parameters of the motion, acquired from the field-testing, were used at both sites investigated in order to verify the suitability of the existing barriers and the possible need for new protection systems.

The tests carried out in the Apennines provided indications about the parameters useful for the computation of block trajectories along a slope located immediately

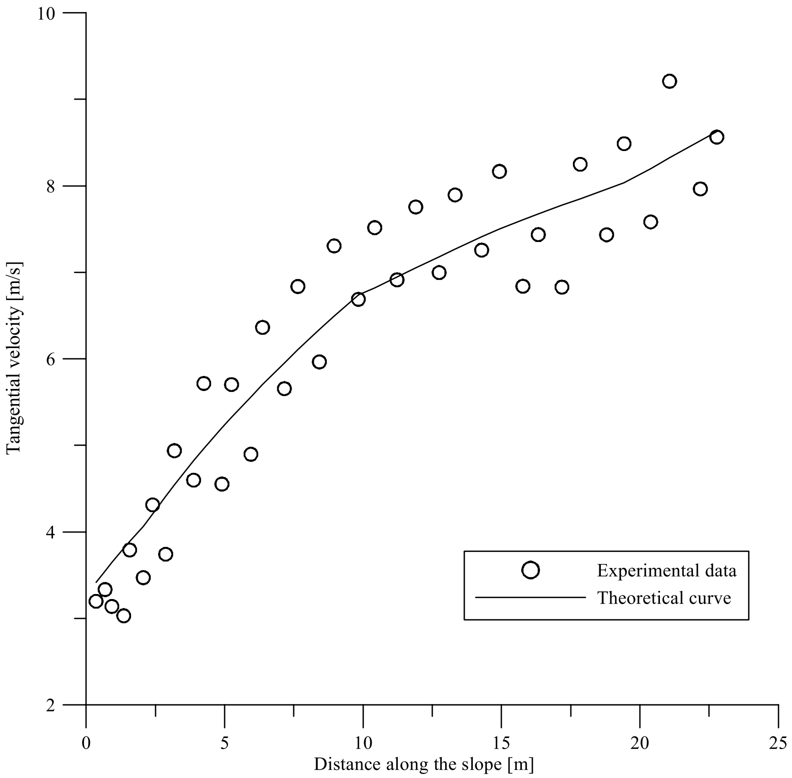

Fig. 11. Comparison between experimental (circles) and theoretical (lines) data for a mobilized block (Alpine site – see Fig. 4)

above the test site. The actual endangered slope could not be used as a test site since, as shown in Fig. 12, it is crossed by a highway.

The analysis of the rock fall potential paths was carried out by using a three-dimensional numerical code at first, and then, once the most critical sections were located, the final calculation was performed using a two-dimensional statistical analysis.

The use of a three-dimensional computational code requires a preliminary site survey for the definition of the areas where the most likely detachments will take place. A topographic and morphological survey of the slope was carried out in order to identify superficially homogeneous areas. The superficial materials identified were divided into four classes: solid rock, blocky clays and compact debris, loose debris (similar to that observed on the test site) and vegetation. The three-dimensional code used, namely ROTOMAP (Scioldo, 1991), allows the analysis of motion along several paths automatically generated from a three-dimensional digital terrain model (DTM).

The ROTOMAP model analyses the free falling and the sliding-rolling motion modes. The parameters governing the motion modes are: normal and tangential coefficients of restitution, and a limit value of the angle that defines the transition from

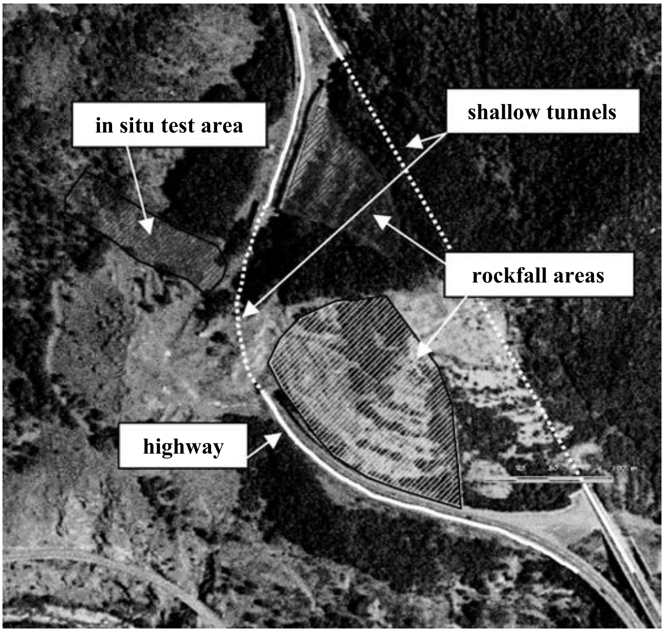

Fig. 12. Aerial photograph of the rock fall in the Apennine area

aerial motion to sliding-rolling motion. This angle is formed between the tangent to the trajectory of a rebounding block and the tangent of the slope profile at the impact point. The transition between bouncing and rolling is established by the ROTOMAP code when this angle is lower than a threshold chosen by the user.

This model can be used when examining a large-scale problem where slope morphology has important variations in the lateral direction and where the endangered area extends over significant lengths. In the numerical model, the slope surface is divided into cells and, for each cell, coefficients are assigned based on the type of surfacing material. The friction and restitution coefficients were assigned by considering the values obtained from the field tests and those suggested by scientific literature (Table 3). The block trajectories, calculated by the three-dimensional model (Fig. 13), show that the rock fall phenomenon along this slope is characterized by a predominant two-dimensional development; in fact, the rock fall paths form narrow bundles of mostly parallel trajectories.

Table 3. Values of coefficients utilized in the 3D computational model (Apennines site)

Surfacing material	k_t	k_n	μ
Solid rock	0.85	0.7	0.4
Compact debris	0.8	0.5	0.5
Loose debris	0.79	0.48	0.5
Vegetation	0.3	0.3	0.7

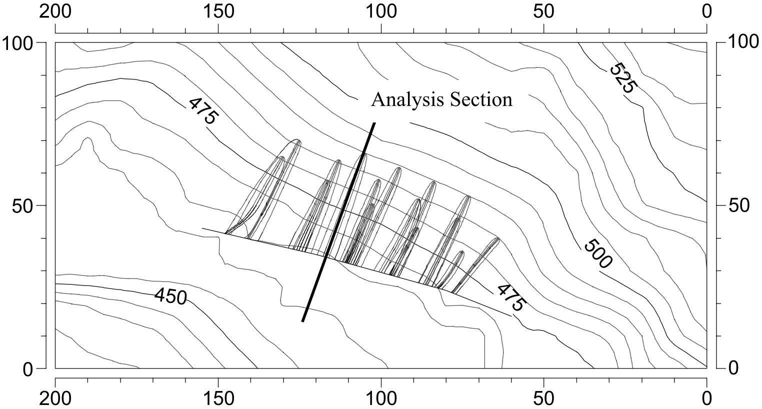

Fig. 13. Rock fall paths resulting from the 3D simulation (Apennines site). The dimensions in m

The results obtained by the three dimensional model are in agreement with the last observed rock fall phenomena occurred in the spring of 2001, when the observed trajectories of fallen blocks were mainly contained in a vertical plane. This allowed to define the most critical sections along which the rock fall path was analyzed by means of a two-dimensional numerical model.

The two-dimensional rock fall simulation was carried out using the CRSP code (Pfeiffer and Bowen, 1989). This code analyzes the path and motion features of blocks descending along the same vertical section of the slope, considering different block volumes and shapes: spherical, cylindrical and discoidal. Therefore, the code calculates the kinetic energy acquired by each block along the path accounting for both rotational and translational motion. For each block the trajectories are analyzed by defining both geometrical position and initial velocity.

The numerical code represents the rock fall motion as a sequence of aerial phases interrupted by impacts and rebounds. The impact phenomenon is described through the imposition of an energy balance. The kinematic features of the motion phases following the impact are determined by the normal and tangential restitution coefficients. For each impact the code assumes a local random variation of the slope angle; the variation magnitude is contained within a range defined by the surface roughness parameter, namely the ratio between the maximum height of the local asperities along the slope surface and the block radius.

The analysis considers the descent of several blocks along each slope section, allowing a statistical evaluation of the motion characteristics at selected distances from the section top.

The primary results of the two-dimensional model are reported in Figs. 14 to 17 in terms of trajectories traveled, average rebound height and velocity acquired by the blocks along the path, and distribution of rebound heights and velocities reached by the blocks at an analysis point selected as tentative position for the protective structure. Figure 14 shows the section chosen for the protective structure tentative position. These results allowed to define design parameters for the protective system.

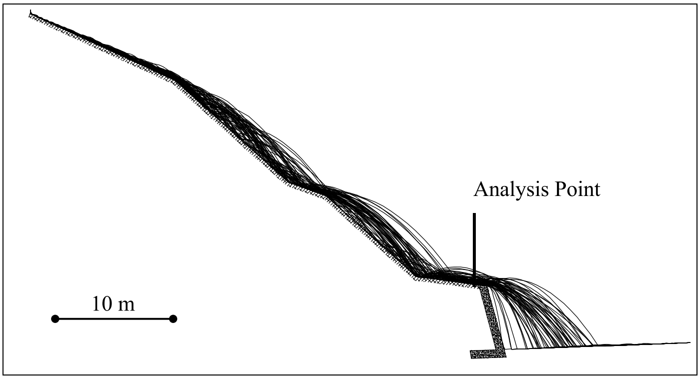

Fig. 14. Rock fall trajectories resulting from the CRSP code simulation along the analysis section reported in Fig. 13 (Apennines site)

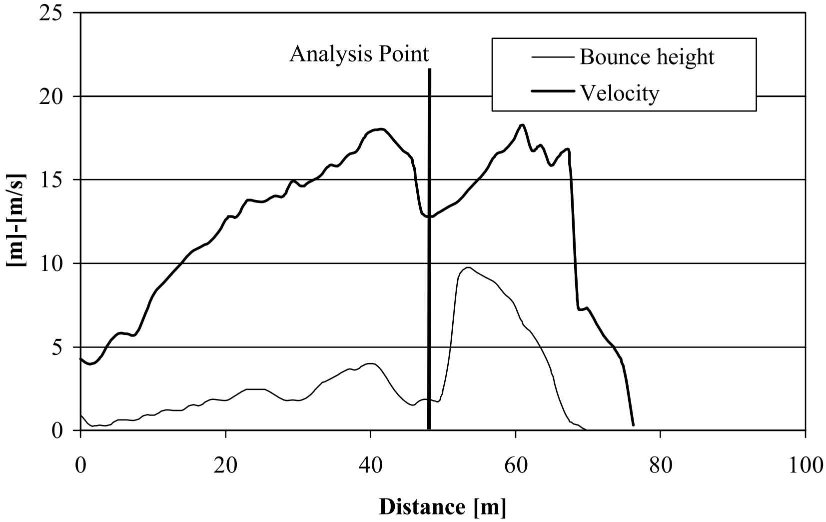

Fig. 15. Height of bounce and velocity vs. distance diagrams (Apennines site)

This system is formed by a barrier, designed on the basis of the numerical modeling results in terms of rebound height and impact energy, associated with other slope modifications such as: scaling and trimming works, slope shaping carried out by the introduction of benches, superficial grid of drainage channels, and application of metallic meshes on the rock walls.

The tests carried out on the Alpine slope involved the actual rock fall endangered area. It was possible to close the road below the slope and directly verify the unstable block trajectories and paths. Here too the numerical model used for the analysis was the two-dimensional CRSP. The validation of the model was carried out by comparing

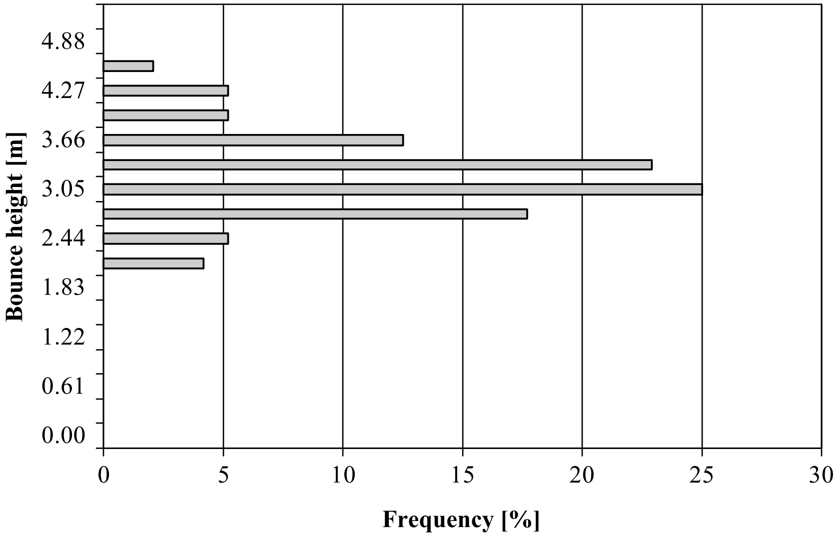

Fig. 16. Distribution of rebound heights reached by the blocks at the analysis point reported in Fig. 14 (Apennines site)

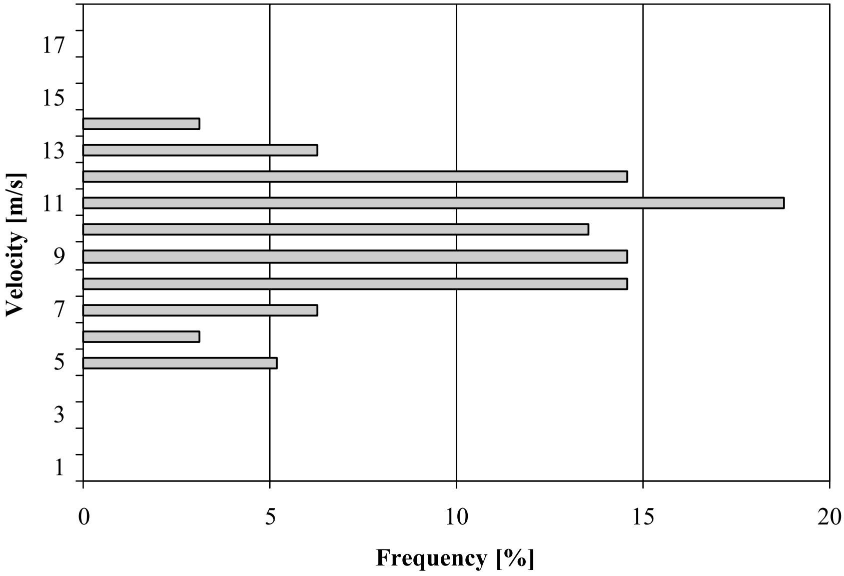

Fig. 17. Distribution of velocities reached by the blocks at the analysis point reported in Fig. 14 (Apennines site)

the paths and trajectories traveled by the block and recorded during the tests, with those obtained from the analysis. The model parameters were experimentally determined. As for the previous site, these parameters are: normal and tangential restitution coefficients, and surface roughness. The slope morphology was defined by means of a detailed topographic survey.

Two different numerical simulations were carried out: in the first model, the whole slope surface was considered homogeneous, as the average motion parameters had been determined during the tests; in the second model, the corresponding restitution coefficients were assigned to each individual portion of the slope section monitored by a single video camera during the tests, as reported in Table 4.

Table 4. Coefficient of restitution values utilized in the two simulations carried out (Alpine site)

Model	1					2
Track	1	2	3	4	5	1–5
k_n	0.1	0.29	0.26	0.69	0.66	0.25
k_t	0.8	0.55	0.68	0.36	0.45	0.47

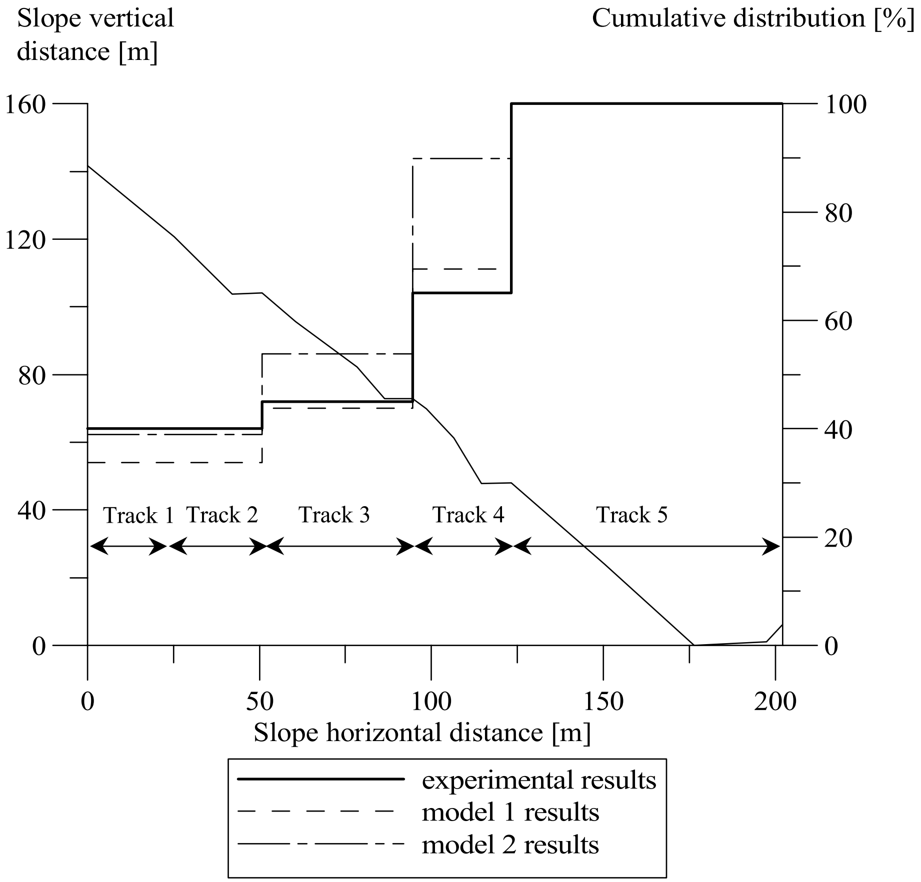

Fig. 18. Cumulative distribution of number of blocks arrested along the slope (Alpine site). Model 1: k_n and k_t variable for the 5 tracks as reported in Table 4; Model 2: constant k_n and k_t (see Table 4)

The initial velocity was assigned taking into account the average falling height of the blocks from the excavator, whilst the block shape was assumed as cylindrical, with dimensions equal to the average of the dimensions measured for the blocks released during the tests. One thousand block trajectories were calculated for each numerical simulation. The comparison between experimental and numerical results was carried out in terms of percentages of blocks stopped at various locations along the slope. The cumulative diagrams reported in Fig. 18 show the arrest zones corresponding to the various berms.

The results obtained by assigning uniform restitution coefficients to the whole slope show a distribution of the arrest zones that involves all three berms and the lower square, although the percentages of arrested blocks are not in agreement with those obtained from the tests. The results obtained using variable restitution coefficients are in better agreement with the experimental observations.

Conclusions

The observation of rock fall phenomena along slopes of various morphology and different superficial material (rock, soil, vegetation, etc.) pointed out how the descent paths of the falling blocks vary in relation to the specific geometrical and mechanical features of both the slope surface and the blocks. These specific properties are generally left out when predictive rock fall numerical analyses are carried out.

The field observations have primarily highlighted the following:

- local variations of the slope roughness and waviness are able to induce significant changes to the paths followed by blocks having similar shape and volume and released from the same position;
- the geometrical configuration of the block has significant influence on the path of travel: the motion efficiency is higher for blocks having spherical shape and smooth surfaces than for blocks having irregular surfaces and sections;
- the relative position of the block at the impact with the slope surface can be extremely favourable for the arrest of the motion if the collision occurs between two plane surfaces or, conversely, can be the cause of limited energy losses if the impact involves the edge of the block;
- the block rotational velocity is a function of its moment of inertia in the section in which the motion is lying: for this purpose an estimate of the volume and geometry of the block must be assessed. Inertial moments of the same block calculated over two orthogonal sections can be so different that, depending on the plane of motion, the length of the traveled path could be extremely variable;
- the fragmentation phenomenon due to the impact of the block on the slope surface frequently causes high energy losses, possibly inducing the arrest of all the block fragments. However, not negligible are the cases in which single fragments, generated from the impact of blocks on the slope surface, are projected in such a way to produce trajectories that are even longer that those of the intact blocks. This situation is due to the formation of fragments with geometrical shape of higher motion efficiency;

- the main features that can be acquired from the video recording of the rock fall tests are substantially of two kinds: those that are deterministically measurable (i.e. normal and tangential coefficients), and those that can be estimated with a certain degree of uncertainty (i.e. surface roughness). The purpose of this work has been to limit the numerical modeling uncertainties to those parameters that are subjectively evaluated.

The parameters needed for the description of the aerial rotation of the block with multiple collisions on the slope surface and those needed for the description of the free fall motion followed by a single impact and rebound were obtained from the field tests. The first motion was modeled using a single coefficient, named the "equivalent rolling coefficient". For the second motion two coefficients were used to describe: (a) the correlation between magnitude and direction of the block velocity before and after the impact, namely the "restitution coefficients", (b) the coefficient which describes the correlation between the slope roughness and the block dimension.

The procedure for numerical modeling of rock fall consists of the following phases:

- three-dimensional analysis of the phenomenon by means of both experimental data analysis and three-dimensional modeling of rock fall, using restitution coefficients for the impact and rebound motion phases, and equivalent rolling coefficient for the aerial rotations and multiple collisions;
- two-dimensional analysis along the critical sections identified during the 3-D analysis and likely to contain most trajectories of the falling rocks. In this type of analysis, restitution and roughness coefficients are assigned for each segment of the slope. The roughness coefficient varied randomly by taking into account that most of the uncertainty involved in the calculation is related to the local morphology of the slope and the relative position of the non-spherical block at impact.

The back analysis performed for the Alpine site, which follows the procedure described above, yields a better result in terms of comparison between the experimental and numerical data when the restitution coefficients are assigned locally along the slope, but not when a single average value is considered for the whole slope. The numerical results show how the relative percentages of blocks arrested at the berms constituting the slope are quite dispersed along the entire length of the block trajectory. It is also shown that in order to obtain a distribution comparable with that observed during the tests, the restitution coefficients should be varied accordingly.

As the on-site survey did not allow to determine the morphological differences of the debris constituting the slope, it would be extremely difficult to predict the values of the parameters governing the rock fall motion without the use of in situ testing.

In conclusion, the authors believe that field experiments are of crucial importance for the evaluation of the parameters governing block impact and rebound phenomena. This is true even if it is currently very difficult to quantify the influence of both, i.e. the slope morphological features and the strength and deformability of the blocks, on the rock fall motion.

The back analysis performed confirms how the procedure described above, covering both on site tests and numerical modeling results, is a valid instrument for both the understanding of this natural phenomenon and the design of rock fall protection systems.

References

Azzoni, A., De Freitas, M. H. (1995): Prediction of rock fall trajectories with the aid of in situ test. Rock Mech. Rock Engng. 28(2), 111–124.

Azzoni, A., La Barbera, G., Zaninetti, A. (1995): Analysis and prediction of rock fall using a mathematical model. Int. J. Rock Mech. Min. Sci. Geomech. Abstr. 32(7), 709–724.

Bozzolo, D., Pamini, R. (1986): Simulation of rock falls down a Valley Site. Acta Mechanica 63, 113–130.

Descoeudres, F., Zimmermann, T. H. (1987): Three-dimensional dynamics calculation of rock fall. 5th Int. Congr. on Rock Mechanics, Montreal, 337–342.

Evans, S. G., Hungr, O. (1993): The assessment of rock fall hazard at the base of talus slopes. Can. Geotech. J. 30, 620–636.

Giani, G. P. (1992): Rock slope stability analysis. Balkema, Rotterdam, 1–361.

Giani, G. P., Migliazza, M. (1999): Indagini e prove in sito per il progetto e la verifica di opere paramassi. XX Convegno Nazionale di Geotecnica su ‘‘Sviluppi nell'esecuzione e nell'impiego delle indagini geotecniche'', AGI, Parma, 475–480.

Giani, G. P., Giacomini, A., Migliazza, M., Segalini, A., Tagliavini, S. (2002): Rock fall in situ observations, analysis and protection works. Int. Symp. on Landslide Risk Mitigation and Protection of Cultural and Natural Heritage, Kyoto, 85–96.

Hungr, O., Evans, S. G. (1988): Engineering evaluation of fragmental rock fall hazard. In: Proc 5th Int. Symp. on Landslides, Lausanne. Balkema, Rotterdam, 685–690.

PFC2D (1999): Particol flow Code in two dimension Version 2.0 – User Guide. Itasca Consulting Group, Minneapolis, USA.

Pfeiffer, T., Bowen, T. (1989): Computer simulation of rock falls. Assoc. Engng. Geolog. Bull. XXVI(1), 135–146.

Piteau, D. R., Clayton, R. (1976): Description of the slope model computer rock fall program for determining rock fall distribution. D.R. Piteau Assoc., November.

Ritchie, A. M. (1963): Evaluation of rock fall and its control. Highway Res. Rec. 17, HRB, National Research Council, Washington, D.C., 13–28.

Scioldo, G. (1991): Rotomap: analisi statistica del rotolamento dei massi. Guida informatica ambientale. Patron, Milano, 81–84.

Shi, G. H. (1989): Block system modeling by discontinuous deformation analysis. Department of Civil Engineering, University of California, Berkeley.

Wu, S. S. (1985): Rock fall evaluation by computer simulation. Transportation Research Record, Transportation Research Board, Washington, DC, no 1031, 1–5.

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