Rockfall distribution and magnitude at the western slope of the Camaldoli Hill (Naples, Italy)

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ABSTRACT: The Camaldoli Hill, located within the metropolitan area of Naples, is highly prone to mass movements and erosion. Rockfall and topple failures are among the most common typologies, and particularly affect the Neapolitan Yellow Tuff (NYT), a volcaniclastic formation widely outcropping in the area. Slope instabilities may detach volumes up to some tens of cubic metres, with individual blocks which frequently reach the urbanized area, as shown by the many historical information on mass movements from national and local archives. Starting from the geomorphologic setting of the Camaldoli Hill, the rockfall distribution and magnitude at its western slope is described. In particular, travel distances of NYT blocks and the related potential of invasion are analysed along selected profiles, and the results cross-checked with the documented evidence of past instabilities.

1 INTRODUCTION

Communities living on active volcanic areas are typically threatened by a number of geological hazards, among which fast-moving slope instabilities (lahars, debris flows and rock falls) hold a prominent position. This is in turn due to either the poor geomechanical properties of loose, unconsolidated pyroclastic products, and to the severe jointing affecting the hard and weak volcanic rocks.

Phlegraean Fields and Mt. Somma-Vesuvius are worldwide known as active volcanic districts, where a population of some million inhabitants lives. Naples partly rests on the eastern side of the Phlegraean Fields and is at about 15 km west of Mt. Vesuvius (Fig. 1). In addition to specific volcanic risks, Naples is exposed to a number of mass movements (Beneduce et al. 1988, Calcaterra & Guarino 1999, Calcaterra et al. 2002).

The Camaldoli Hill (458 m a.s.l.) is the highest peak of the Phlegraean Fields, impending over some densely populated districts of Naples. Most of the recorded landslides affecting the hill regards recent events (from 1950s onwards), the majority of which are rainfall-induced slides-flows which occurred in 1996 and 1997. However, rock slope instabilities are also a common process, due to the presence of vertical cliffs in highly fractured tuffs. In this paper, the focus is on the hazard posed by rock falls to the settlements at the western foothills of Camaldoli, where in recent years a plan devoted to mitigation of the landslide and hydraulic hazards has been promoted by the Municipality of Naples.

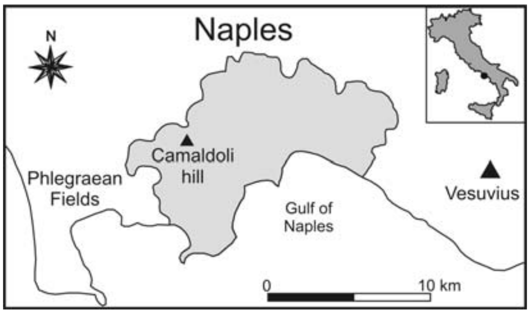

Figure 1. Location of the study area.

2 GEOLOGY

The Camaldoli western slope displays a large portion of the Phlegraean volcanic sequence, ranging in age between 60 ka and AD 1538 (Orsi et al. 1998). In the study area volcanic formations dated between 39 and 3.8 ka crop out (Calcaterra & Orsi 2003). They are, from the oldest:

- Campanian Ignimbrite (CI – 39 ka) represented by Piperno Fmn. (welded tuff, with dark grey flattened scoriæ in a light grey ashy matrix), locally overlain by heterometric coarse-grained breccias (Breccia Museo Fmn.) and by prevailing loose ignimbrites. The base of this formation is not exposed and its maximum thickness is about 20 m;
- Whitish Tuffs (39 – 18 ka): whitish ash and pumice layers and lenses, with variable welding de-

gree and plane-parallel to sandwave and cross-laminated ash beds. Max. thickness: about 50 m;

- Soccavo Tuff (18 – 12 ka): lithified sequence of laminated ash and pumice layers and lenses, yellowish in colour. Max. thickness: 40-50 m;
- Neapolitan Yellow Tuff (NYT – 12 ka): lithified, highly fractured sequence of yellow ash layers, from massive to laminated, including pumice and lithic fragments. Thickness: 20 to about 100 m;
- Pyroclastic deposits (12 – 3.8 ka): fall and subordinately surge deposits, made up of ashes, pumice and interbedded palaeosols, referred to more than 20 eruptions (Di Vito et al. 1999). The whole sequence generally mantles the underlying NYT, with thickness from a few to about 30 m;
- Talus, landslide and basal plain deposits, with thickness from 0.5 m (on the slopes) to some tens of metres (in the plain).

On the gentler slopes, bedrock formations are mantled by a thin cover of epiclastics and pyroclastics, ranging from 0.5 to 5 m in thickness, and deriving from dismantling of the 12 – 3.8 ka deposits.

Two main systems of faults and major joints are recognizable in the area, respectively oriented N-S and N 80° E, along with a third, subordinate set (N 40° W).

3 GEOMORPHOLOGY

The geomorphologic study was performed by means of a field survey at a 1:1000 scale, integrated by airphoto interpretation. The main morphological features of the Camaldoli Hill are represented by several subvertical cliffs, whose origin can be structural or related to the different response to erosion of exposed lithologies. Zeolitized pyroclastics, NYT, Soccavo Tuff and Whitish Tuffs, show vertical cliffs, while the gradient is much lower where the loose deposits crop out. Among the tectonically-controlled cliffs, the most evident is that one between altitudes of 300 and 400 m a.s.l., which took origin from the parallel retreat of a fault plane in the NYT, and has therefore to be dated after its emplacement, somewhere between 12 and 9.5 ka.

The transverse profile of the Camaldoli Hill can be subdivided ideally into four different sectors (Fig. 2): the top highplain, the main slope, the footslope, and the basal plain.

The top highplain is a low inclined NW-dipping surface at elevations between 300 and 460 m a.s.l. Besides the topographic position, it was characterized in the last decades by heavy anthropogenic works which resulted in strong changes of the original morphology. Anthropization is also at the origin of the diffuse environmental degradation and pollution, since from the inhabited areas solid wastes are illegally dumped into the valleys below, and liquid wastes are discharged along the main water lines.

The main slope is that part comprised between the top highplain and the footslopes. In turn, it can show two different characters in the area: planar slope, and deeply incised slope. In the first case, the slope is generally open and presents valleys with a limited development. Incised slopes are, on the other hand, characterized by deep valleys which terminate just above the inhabited area of Pianura and Soccavo, often in correspondence with those areas which were devoted in the past to quarrying activity. Quarries caused heavy changes in the original morphology, and today they present thick filling of debris derived from the past activity.

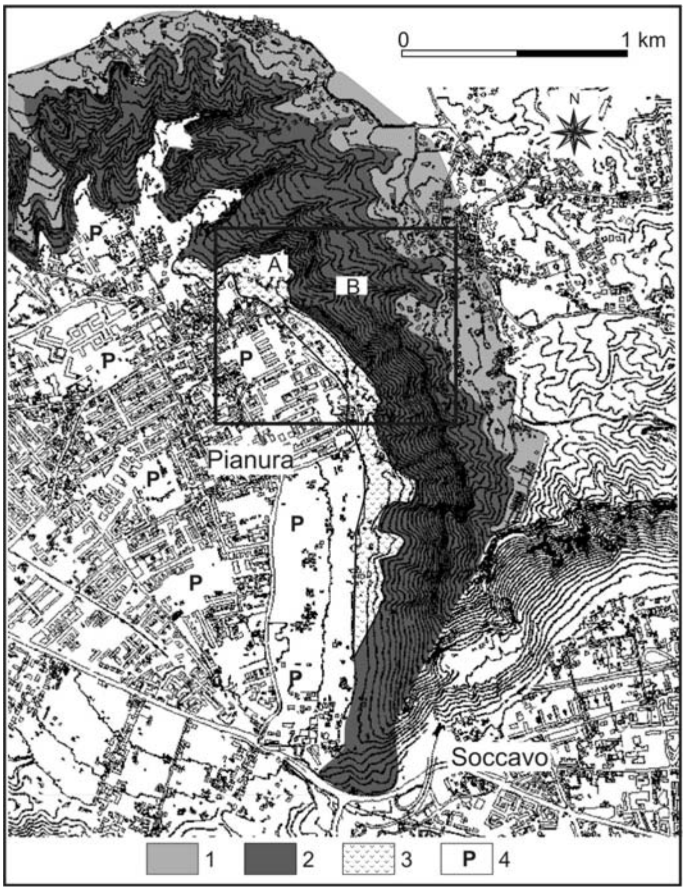

Figure 2. Geomorphologic zonation of the Camaldoli Hill, western slope. 1) Top highplain; 2) Main slope; 3) Footslope; 4) Basal plain. A: Church *Piccola Lourdes*; B: *Vallone S. Antonio*. The inset refers to Figure 5.

The valleys are up to 800-900 m long, and with longitudinal gradients that often are above 40-60°, locally reaching the verticality at the cliffs in the more lithoid materials. They are strongly controlled by tectonics, as evidenced by the linear path, the sharp bends, and the frequent, up to some metres high, vertical steps in the transverse profile. In many cases solid wastes mixed with landslide deposits have been observed within the valleys. These wastes have probably had a role in favouring instability in the area, due to the overcharge they exert on the slopes. In addition, their presence in the valleys may cause, during rainfall, remobilization and downvalley transport, so increasing the overall volume of solid material; or, alternatively, create obstructions, causing the accumulation of further materials upvalley, with the likely consequence of sudden release of large amount of mixed deposits.

The footslope is the transition zone between the main slope and the plain where the inhabited area develops. This sector originated from the accumulation of debris which resulted in the formation of fans fed by different genetic processes (erosion, mass movements). Proximity of this sector to the inhabited area caused heavy changes in the original morphology of the fans, such that nowadays their recognition is not easy. Quarrying and terracing for agricultural purposes were, in particular, the main actions which deeply changed the natural configuration.

The basal plain is the sector where the inhabited area is located. Morphologically similar to the top highplain, it is flat and heavily anthropized. Uphill, the connection with the footslope is gradual, through a number of terraces. The portion of the plain closer to the footslope may be involved by arrival of deposits on the occasion of landslide and flood events.

4 SLOPE INSTABILITY

At Camaldoli, slope instability consists of several small to medium-size slides, and of rocks falling and toppling from the vertical cliffs. Shallow slides affect mostly the surficial pyroclastic cover, involving thickness in the order of 0.5÷1 m in the more weathered, generally loose, portions. Triggering is usually given by rainfall or by anthropogenic activities on the slopes. The risk related to this type of landslide depends upon their occurrence in areas close to the inhabited areas (the footslope and the rims of the top highplain) and upon their possible evolution into channelized debris flows.

Vertical or near to vertical walls in lithified materials are frequently affected by detachment of blocks with fall or topple typologies. Failure is controlled by the main discontinuity systems in the rock mass, which determine the detachment of extremely variable volumes of rock. The spatial relationship between fracturing of the rock and geometry of the wall controls the mechanism of movement. At many sites, even locally just above the inhabited areas, open fractures are visible in the rock walls, which could evolve into detachment zones of further rock falls. Almost all the steepest cliffs which are present at various heights along the Camaldoli slope are affected by these phenomena. The vicinity in many cases of anthropogenic infrastructures (including houses) to the cliffs, combined with the high susceptibility of the materials to failures, determines high vulnerability and high specific risk. The most hazardous situations are:

- all the quarry walls and the majority of rock walls, with particular reference to those above the Church *Piccola Lourdes* and the buildings in the Vallone Sant'Antonio;
- some sectors located immediately downvalley of the main slope.

In these areas recent falls have been observed. As an example, on April 5, 2002, following intense and concentrated rainfall, a rock fall occurred in the proximity of the Church *Piccola Lourdes*, involving materials of the Campanian Ignimbrite (Fig. 3).

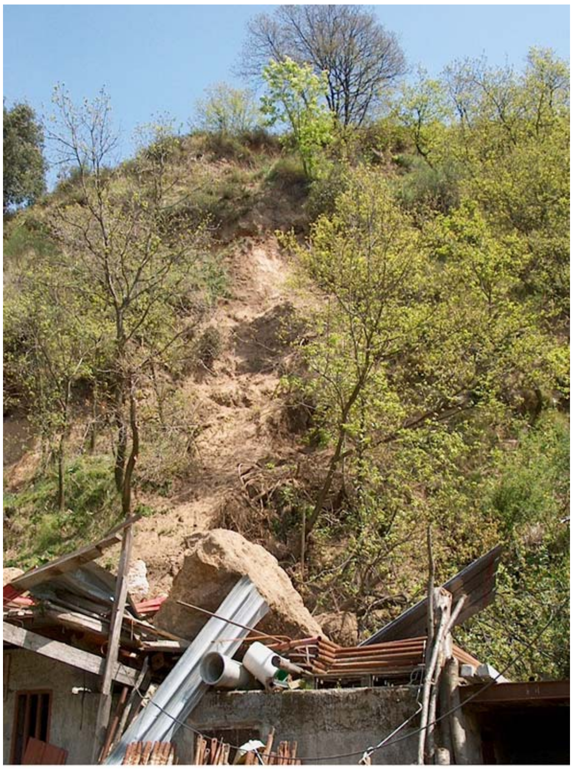

Figure 3. Rock fall in Campanian Ignimbrite, occurred on 5 April, 2002 near the Church *Piccola Lourdes*.

Figure 4. Example of block stopped by trees at the footslope. Block volume is about 0.5 m^3.

Topography downslope from the detachment zone controls the evolution of the mass movements after the initial phase of fall or topple. In the case of slope with more or less gradual gradient downvalley, detached blocks may move and travel for long distance. However, they may frequently rest on the slope below the detachment zone, after a more or less brief travel, as shown by the several blocks that are visible on the planar slope of the Camaldoli Hill. Some blocks, on the other hand, are able to acquire velocity and keep travelling downvalley, reaching the footslope area: there, the man-made terraces and the vegetation are important elements for the mitigation of the risk, since they can stop or cause a decrease in the velocity of the blocks (Fig. 4).

In the northern sector of the study area, due to the high gradients, detached blocks generally reach the valley bottoms, where they feed landslide debris which can be later re-mobilized on the occasion of floods and/or intense rainfalls.

The highest frequency of fallen boulders has been observed in the area depicted in Figure 5, where the distribution of the main blocks is shown. Further evidence of the potential invasion of rock falls is displayed by some recently excavated trenches: there, blocks prevailingly belonging to NYT have been found, which allows to infer that the maximum travel distance is on the order of 200-250 m from the main scarps. Consequently, H/L values range between 0.7 and 0.8, corresponding to angles of reach from 35° to 40°. These values denote a quite high mobility of NYT blocks, which confirms the tendency, already evidenced in literature (e.g. Corominas 1996), toward an excess of travel distance for small-scale rockfalls.

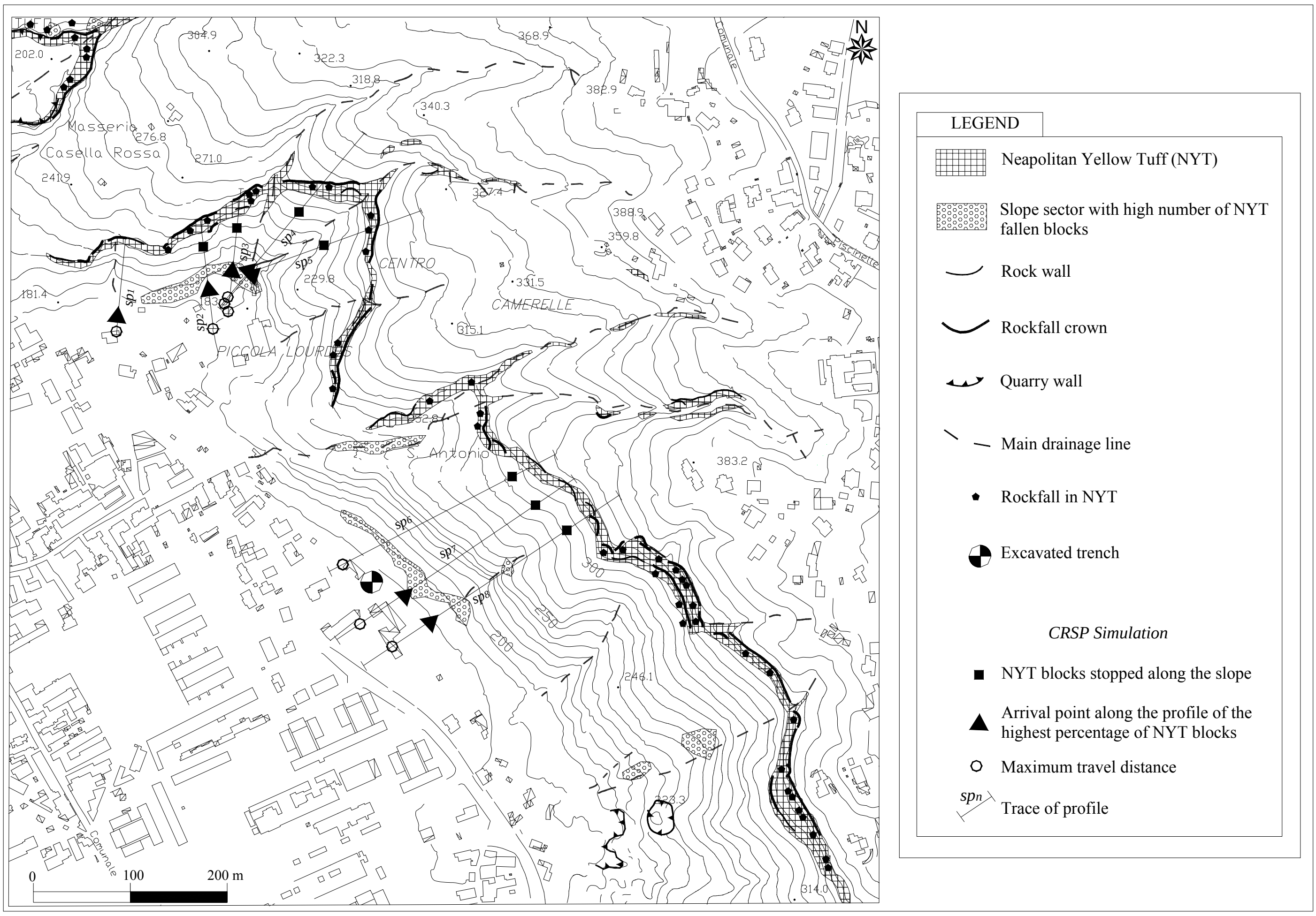

Figure 5. Plan view of the middle sector of the Camaldoli Hill, western slope. Comparison between field evidence and CRSP results in terms of NYT rockfall potential of invasion. Geological data after Calcaterra & Orsi (2003).

5 ROCKFALL HAZARD BACK-ANALYSIS

5.1 *General considerations*

The use of mathematical models to predict the path of blocks along a slope is useful to assess the hazard related to rock falls, and to evaluate the vulnerability of the elements exposed at risk. Validity of an analytical model depends generally upon two factors: a) description of the physical phenomena occurring during the path, and b) reliability of the parameters chosen to determine the aforementioned phenomena. Two types of previsional analytical models are available: methods which consider as fallen block a unit mass (the so-called *lumped mass methods*), and, on the other hand, methods which allow to include in the analysis both shape and size of the blocks.

Several types of movement may occur after detachment of a rock: free fall, impact and bouncing on the slope surface, rolling, sliding. The more delicate step in modelling regards the selection of those conditions controlling the transition from one type of movement to the other, and the description of the block behaviour at the impact. In this study the used model refers to movement of a single block which is detached from the wall and moves along the slope with no interactions with other blocks.

The programme CRSP *(Colorado Rockfall Simulation Program;* Pfeiffer & Bowen 1989, Jones et al. 2000) was used to predict the exposure to rockfall hazard. CRSP is a stochastic numerical model that simulates the behaviour of block motions. It was elaborated to model the fall of blocks in shape of spheres, cylinders or disks, with a circular section in the vertical plane of movement. The programme provides statistical analysis of velocity, kinetic energy, and height of rebounds at several sites of the slope. Movement of the rock along the slope is described by means of the equation of parabolic motion of a body, and the principle of conservation of the energy. The dynamic interaction between the rock and the slope is analyzed by means of empirically derived functions on velocity, friction, and physical properties of the slope materials. The parameters required by the programme to model the impact of the rock on the slope are: normal and tangential coefficients of restitution, slope roughness, and block size. The assumptions on which the algorithm is based are:

- all the computations are made in 2D;
- the programme has the capability to consider the shape and size of the block, which are both assumed constant;
- the slope geometry is input as a series of straight-line segments, referred to as cells, each characterized by uniform parameters, such as slope gradient, surface roughness, normal (Rn) and tangential (Rt) coefficients of restitution;
- surface irregularities are modelled by randomly varying the slope angle between limits set by the rock size and surface roughness (Wu 1984).

5.2 *Implementation at the Camaldoli Hill*

In the back-analysis performed by means of CRSP, the following elements were taken into account: position of fallen blocks on the slope; evidence from trenches; information on previous rock falls. The main aim of the simulation was to predict the maximum potential of invasion of blocks detached from NYT cliffs and to compare these results with the available data. Hence, a back-analysis was conducted, whose objective was the definition of suitable restitution coefficients and surface roughness needed to fulfil the field evidence, given the geological and morphological assumptions above.

The data collected during the structural surveying have been elaborated by means of the *Geo&Soft* program CLU_STAR, which is able to identify the main discontinuity systems through a cluster analysis. The kinematic feasibility of rock slope instability mechanisms was then performed at each station. At NYT outcrops, three to four joint systems have been recognized, one of which is given by a low-angle set (tuff beds), showing dip angles in the range from 10° to 30°. Accordingly, wedge failures proved to be feasible, as displayed in Figure 6, along with toppling.

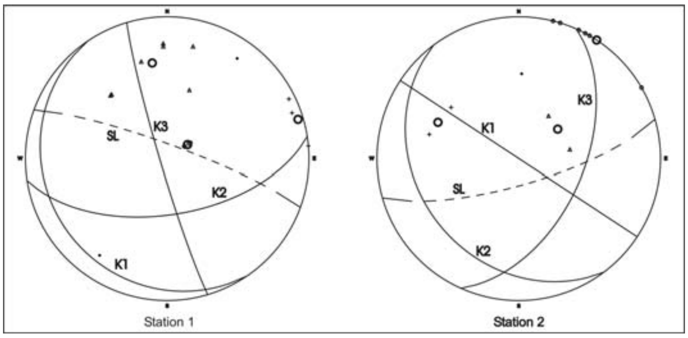

Figure 6. Stereonets of some geostructural stations in NYT. SL = slope face; Kn = joint system.

Once known the spacing of the main discontinuity systems, it has been possible to reconstruct shape and size of the potentially unstable blocks.

Since the geo-mechanical parameters are function of the slope characteristics (gradient, material, presence and type of obstacles, etc.) and blocks (shape, size, material), a back-analysis based upon the maximum travel distances of blocks observed in the field was performed to identify the values to be assigned to the restitution coefficients.

Volume of fallen blocks identified in the field ranges from 0.50 to 2.00 m^3; thus, diameter of the blocks has been considered as ranging from 1 to 1.6 m. At each profile, 200 simulations have been performed. The results were calibrated by comparing the stop points as assessed by CRSP with the main areas of blocks resting on the slope. This procedure resulted in obtaining Rn values equal to 0.3 ÷ 0.4 and Rt values between 0.3 and 0.5. Profiles 1 to 5 show coefficients of restitution lower than profiles 6 to 8. This result is strictly related to thickness of the pyroclastic and detrital cover on the slope (respectively, < 1 m at profiles 6 to 8, and > 5 m at profiles 1 to 5).

As known, Rn and Rt may vary in a quite wide interval (Rn = 0.2÷0.9; Rt = 0.2÷0.99, Richards 1988), chiefly depending upon the rock behaviour at impact. Rn and Rt values obtained by means of our back-analysis seem well-consistent with the literature data, and generally referable to a bedrock covered with soft soil and/or vegetation or, alternatively, to compact detrital material mixed with small boulders (Piteau & Clayton 1977).

The simulated rock falls displayed a variable potential of invasion, controlled by the overall slope geometry and by the height of the NYT scarps. In fact, in the *Piccola Lourdes* area, the maximum reach is in the 90÷160 m interval, while at the profiles 6 to 8, 220÷260 m from the source zone have been travelled..

Maximum velocities range from 25 to 30 m/s at specific sites of profiles 3, 5 and 6. Rebound heights are between 0 and 24 m, the maximum height being registered along profile 6, where bare outcrops of Soccavo Tuff are present. The kinetic energy appears to vary greatly, essentially as a function of the block volume; descending boulders smaller than 1 m^3 reach values up to 675 kJ, while for volumes between 1 and 2 m^3 1350 kJ are attained.

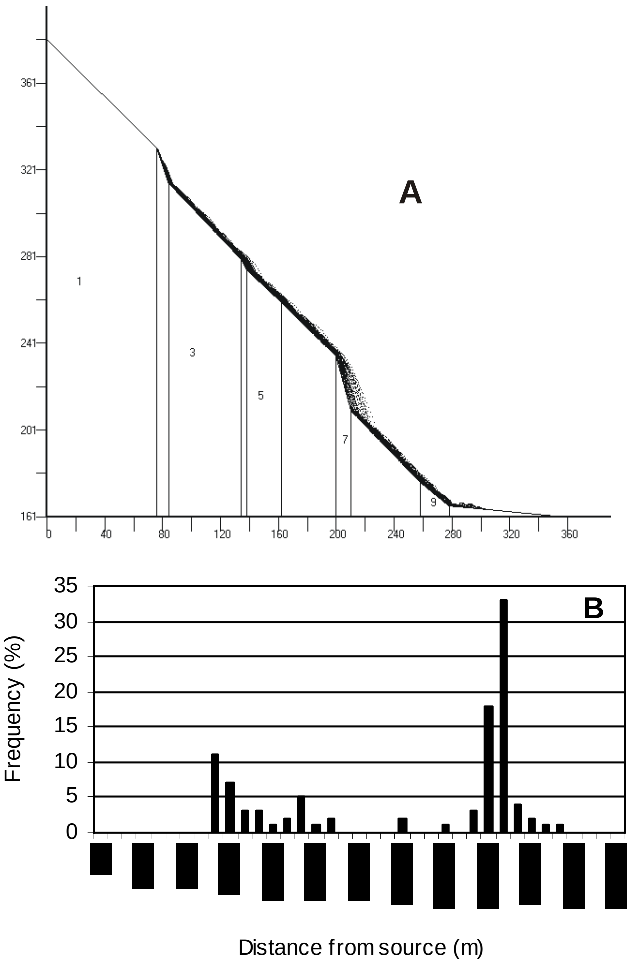

Figure 7. CRSP slope profile no. 7. A) Results of rockfall simulation; B) Frequency distribution of stop points.

6 CONCLUSIONS

2D and, more recently, 3D simulation procedures represent the crucial step in the assessment of the rockfall hazard. Nowadays, availability of GIS-supported codes allows to consider a single vertical section, and, above all, to produce rockfall hazard maps.

However, a major drawback usually affects rockfall analyses, which is given by the input of realistic coefficients of restitution. Still scarce is in fact the overall database concerning these parameters, which should cover a great variety of geological and geomechanical situations. The need for appropriate Rn and Rt values is therefore still urgent for both researchers and practitioners, and can be usefully fulfilled following two main directions. The first approach is represented by empirical studies of rock falls, typically based on full-scale rockfall field-tests, during which boulders are dropped, rolled, filmed and consequently analysed. By doing so, site-specific parameters can be derived, which govern rockfall trajectories and behaviour. As evident, this method is hardly applicable when urban settlements or infrastructures lie at the immediate footslope. On the other hand, back analyses can greatly help in obtaining reasonable information, provided that a robust set of geological and geomorphologic data is available.

The case of the western slope of the Camaldoli Hill has been tackled adopting a back-analysis, performed with the help of the well-known CRSP code. Accordingly, tentative parameters were selected to obtain reasonable agreement with field observations. The resulting geomechanical parameters displayed a good correlation also with the literature data. As regards the potential of boulder invasion, expressed in terms of travel distance, CRSP predictions well matched the field evidence, being only affected by a tendency to depict a slightly worst scenario, as already evidenced in other settings (Jones et al. 2000).

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