Geogr. Fis. Dinam. Quat.
31 (2008), 215-223, 8 figg., 1 tab.

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APPLICATION OF EMPIRIC MODELS FOR THE ANALYSIS OF ROCK-FALL RUNOUT AT A REGIONAL SCALE IN MOUNTAIN AREAS: EXAMPLES FROM THE DOLOMITES AND THE NORTHERN APENNINES (ITALY)

ABSTRACT: PIACENTINI D. & SOLDATI M., *Application of empiric models for the analysis of rock-fall runout at a regional scale in mountain areas: examples from the Dolomites and the northern Apennines (Italy).* (IT ISSN 0391-9838, 2008).

Rock falls are common in mountain areas and represent a serious threat due to their high propagation velocity that, independently from the volume involved, can be extremely dangerous for buildings, roads and persons. Therefore, it is necessary to preliminarily identify the areas most prone to this type of process, in order to pursue a territorial planning with consciousness of hazards and risks. Rock-fall hazard analysis over wide territories is anyhow rather difficult, because many variables have to be taken into account (i.e., fracturing of rock masses, presence of water etc.) that are difficult to identify at that scale. Hence the necessity to identify methodologies of analysis capable of reproducing the complex processes that are involved in rock-fall occurrence and propagation and to preliminarily identify the areas most susceptible to this type of hazard.

Taking into account previous works carried out on this topic, different simulation models, both empirical and kinematic, have been analysed in order to assess their suitability (in terms of quality, time and costs) when applied over wide territories. The most suitable model was found to be an empirical one that assumes the dissipation of rock-fall energy proportional to the distance reached by the falling rock mass. This model has been used, after a specific calibration, with reference to two different study areas characterised by different geological and morpho-climatic characteristics, in order to assess its applicability and validate the quality of the results. The study areas are located in the Dolomites and in the northern Apennines (Italy).

The comparison of the results obtained with respect to the two study sites has shown that the empirical model selected can be an efficient analysis method to obtain reliable results over wide territories, independently from the geological and morpho-climatic characteristics of a certain study site.

KEY WORDS: Rock falls, Runout, Empirical models, Dolomites, Apennines, Italy.

INTRODUCTION

Steep rock cliffs can be affected by rock falls that, due to their high velocity, can be very dangerous, independently from the volumes involved. This type of landslide can cause relevant damages to built-up areas and threaten human lives. Therefore it is of paramount importance to predict their runout for a correct land management. This is a rather difficult task, particularly at a regional scale, because the most well-known methods are applicable only in small territories and generally along pre-defined fall profiles that do not contemplate lateral diffusion.

For this reason the Geomorphology Group of the University of Modena and Reggio Emilia, in the framework of agreements with public agencies, has undertaken studies to achieve a cost-effective analysis methodology to be applied over wide territories, which did not necessitate a relevant amount of input data and could lead anyhow to reliable results.

This paper illustrates the results deriving from the application and calibration of this kind of methodology for the calculation of the runout of rock falls using a GIS. A 3D empirical model has been adopted, calibrated and validated through comparisons with the results of kinematic models and field checks. The method has been applied in two areas with different geological and morpho-climatic characteristics, in the Dolomites (Province of Bolzano) and in the northern Apennines (Romagna region). Those areas were considered as suitable test sites for vali-

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The research has been funded by the «Ufficio Geologico e Prove Materiali» of the Provincia Autonoma di Bolzano», by the CARG-PAB Project for the hazard mapping of the Sheet 028 «La Marmolada» and by the «Autorità dei Bacini Regionali Romagnoli». We are thankful to the «Servizio Geologico Sismico e dei Suoli» of the Emilia-Romagna region for the collaboration established.

dating the method since both of them are affected by several rock falls.

STATE OF THE ART

Different numerical models aiming at reproducing the process of rock falling can be used to analyse how blocks move along a slope and, consequently, to estimate the runout distance. Nevertheless, relationships between geomorphological parameters and the trajectories of the blocks are not easy to identify and even small variations in the initial input data can lead to relevant, and sometimes unpredictable, variations in the final results.

Throughout the years, several models for the analysis and prediction of rock falls have been proposed. Among those, the most common are empirical or kinematic ones. Empirical models, such as those proposed by Onofri & Candian (1979), Heinimann & *alii* (1998), Jaboyedoff & Labiouse (2003) and Piacentini (2006), assume energy dissipation proportional to the length of the rock-fall runout distance. Based on the historical analysis of rock falls, they are easily applicable and suitable to make a first estimate of the maximum runout as a function of the slope topography. Kinematic models analyse instead the maximum runout of blocks considering the physics of motion and its relative equations, though with some necessary simplifications (Cocco, 1991; Azzoni & *alii*, 1995; Paronuzzi & Artini, 1999; Guzzetti & *alii*, 2002; Agliardi & Crosta, 2003; Del Maschio & *alii*, 2004; Geo&Soft, 2004; Crosta & *alii*, 2006). They are based on different algorithms that describe the relationships between the type of motion (fall, bouncing, rolling and sliding), energy of the blocks and slope coefficients. The kinematic models, in spite of uncertainties related to the choice of the motion parameters, have the advantage to allow simulations that reproduce the landslide behaviour, calculating trajectories, velocities and kinetic energies of blocks during their motion, which are fundamental for territorial planning and for the design of mitigation works.

Previous studies concerned with the application at different scales of empirical and kinematic models in different geological and morpho-climatic contexts have shown that empirical methods are preferable for wide-area analyses because of their easy applicability and the need of limited input data, while kinematic models are preferable for detailed studies, due to the need of large amounts of input data (Del Maschio & *alii*, 2007).

STUDY SITES

Two large areas showing different structural and morpho-climatic conditions, but both characterised by several rock falls, have been selected in order to apply an empirical model that appeared to be the most suitable over wide territories. The aim has been to compare the results achieved and to validate the investigation methodology. The abundant number of past rock fall events was the most important common characteristic of the two sites for the calibration of the method with respect to each area.

The study sites are located in the Dolomites (Province of Bolzano) and in the northern Apennines (Romagna region) (fig. 1).

The dolomitic area selected is characterized by a high relief energy. Sub-vertical rock cliffs, made up of dolostones, limestones, marls and porphyries, outcrop on top of weak rocks that give smoother morphologies. The climate is typically alpine: winter is relatively long and very cold, while summer is short and temperate. Within this climatic environment, frost shattering processes and the partial melting of permafrost play a fundamental role in favouring the detachment of rock fragments and blocks from rock cliffs.

On the other hand, the landscape of the Romagna Apennines shows a more regular morphology and gradual transitions between lithotypes. In this area, sedimentary rocks, mainly sandstones, marls and clays, characterize the majority of the slopes. The climate is humid-temperate, characterized by mild winters and rather hot summers. In this climatic environment, the causes of rock falls have to be sought mainly within the geological structure and are more related to water presence than to frost shattering processes.

THE STUDY AREA IN THE DOLOMITES

The study area in the Dolomites belongs to the Autonomous Province of Bolzano and includes the Gardena and Badia valleys which are located near the boundary with the provinces of Trento and Belluno. The study area is 250 km^2 wide and includes the municipalities of Corvara in Badia, Selva di Val Gardena, S. Cristina, Badia and Ortisei.

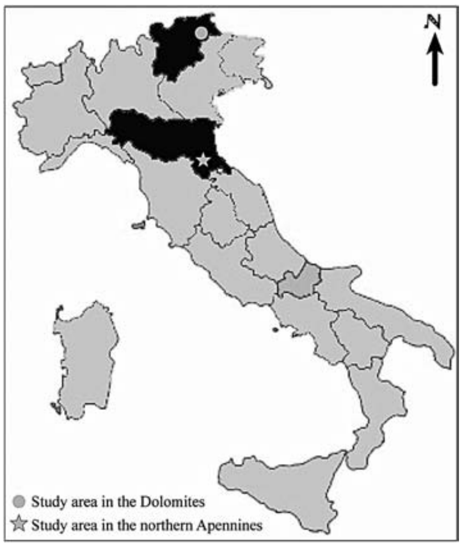

FIG. 1 - Study sites.

The test site comprises important massifs such as Sella (3151 m a.s.l.), Puez-Odle (3025 m), Sasso Piatto (2853 m), Sasso Lungo (3179 m), Croda di Santa Croce (2673 m), Lavarella (3055 m) and Conturines (3064 m) where rock falls are very frequent and abundant along the rock cliffs.

The landscape is characterised by the typical geological features of the Dolomites, in terms of lithology and tectonics, and widely shows the evidence of the different morphogenetic processes acting during the Quaternary due to glaciers, running waters, gravity, frost and, last but not least, man (fig. 2).

The rock outcrops of the area mainly consist of sedimentary and volcanic rocks formed from the Permian to the entire Cretaceous. The morphology of the territory is strictly controlled by the structure and is characterized by high sub-vertical rock cliffs (e.g., Puez-Odle, Sella), reaching some hundreds metres of height, and smoother slopes.

The oldest rocks outcropping in the area (mainly north-west of Ortisei) belong to the volcanic formation of the Porfidi Quarziferi. The geological sequence includes then sedimentary formations derived from the erosion of the latter (e.g., Val Gardena Sandstones, Richthofen Conglomerate), and others deposited after subsequent marine transgressions (e.g., Bellerophon Formation, Werfen Formation, Sciliar Dolomite, Cassian Dolomite, Dolomia Principale), alternating with intra-basin lithotypes (e.g., Livinallongo Formation, S. Cassiano Formation). The most recent rocks belong to the formations of Ammonitico Rosso and Marne del Puez, typical of deep-sea sedimentation.

In this territory, rock falls mainly affect steep slopes made up of dolomite and calcareous rocks (Sciliar Dolomite, Cassian Dolomite, Dürrestein Dolomite, Dolomia Principale, Morbiac Limestones, Dachstein Limestones and Ammonitico Rosso), as well as other types of rocks, such as those belonging to Marne del Puez, Livinallongo Formation, Porfidi Quarziferi and Richthofen Conglomerate (fig. 2). These rock types are, in fact, characterised by hard consolidated rocks whose stability depends on the density and orientation of joints and on the periglacial processes acting on them, mainly linked to permafrost degradation and to frost shattering phenomena.

THE STUDY AREA IN THE NORTHERN APENNINES

The study area in the northern Apennines includes the Romagna mountain reliefs from the Apennine watershed to the Adriatic Sea. The study area is 2329 km^2 wide and includes 25 municipalities belonging to the provinces of Ravenna, Forlì-Cesena and Firenze.

The area comprises important Apennine peaks such as Mt. Fumaiolo (1408 m), Mt. Falco (1658 m), Mt. Gabrendo (1539 m), Mt. del Becco (1005 m) and Poggio Scali (1520 m). The morphology is strongly influenced by the geological features of the region, namely by the the geomechanical characteristics of outcropping rocks, the attitude of strata and the recent tectonic activity, which is also witnessed by the high seismicity of the area. The strong differences in height between mountain crests and the deeply incised valley bottoms, the geometry of the hydrographical pattern, the presence of landslides mainly on slopes affected by thrusts or faults prove a strong tectonic control in the geomorphological evolution of the area. Active morphogenetic processes are mainly related to running waters, slope instability and human activities (fig. 3).

The geological formations outcropping in the area have a marine sedimentary origin and belong to four main sequences: the Toscana sequence (e.g., Scaglia Toscana and Macigno), the Umbro-marchigiana-romagnola sequence (e.g., Formazione Marnoso Arenacea and Marne di Verghereto), the Ligurian unit (e.g., Val Savio Melanges, Ar-

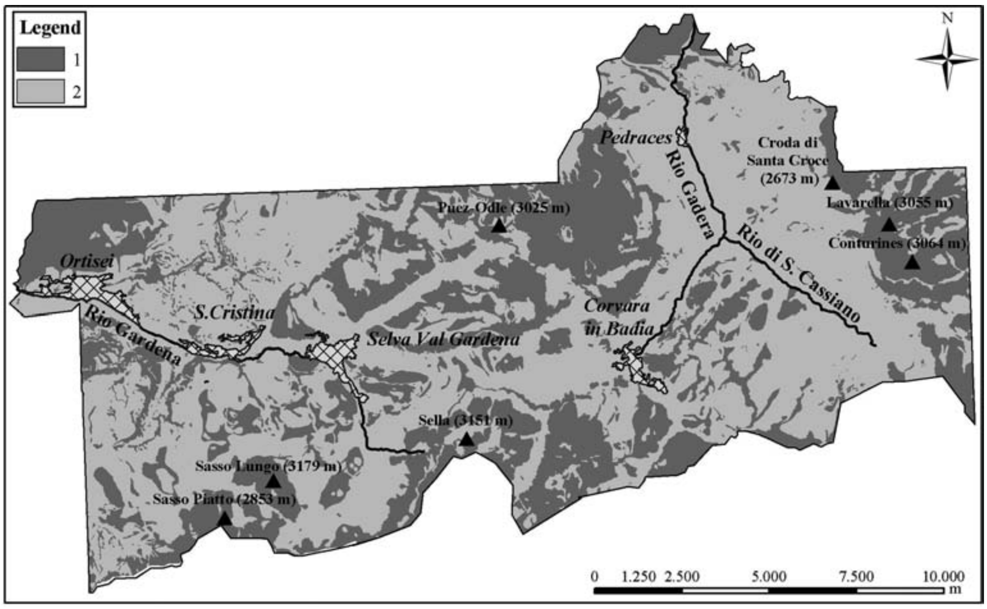

FIG. 2 - Simplified geological map of the study area in the Dolomites. Legend: 1) Rock types affected by falling; 2) Other rock types.

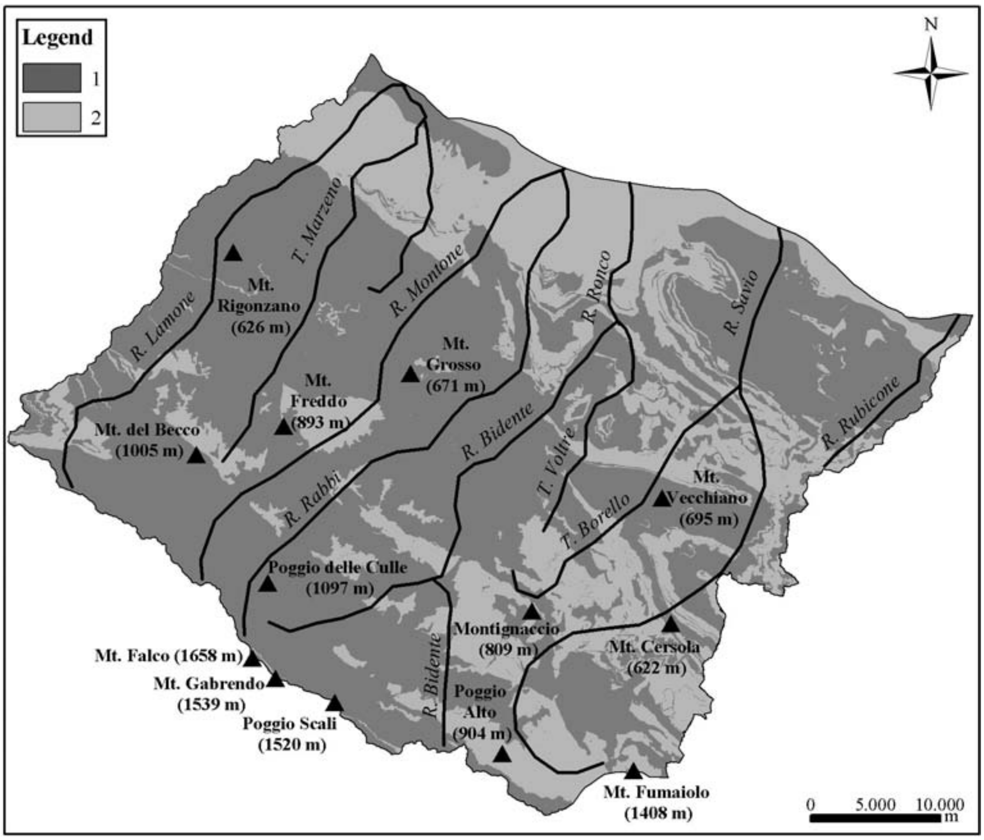

FIG. 3 - Simplified geological map of the study area in the northern Apennines. Legend: 1) Rock types affected by falling; 2) Other rock types.

gille Varicolori della Val Samoggia) and the Epiligurian unit (e.g., Mt. Fumaiolo Formation, Poggio Carnaio Sandstones).

In the study area, the Umbro-marchigiana-romagnola sequence consists mainly of Upper Oligocene-Middle Miocene thick siliciclastic turbidite sequences and of chaotic shaly assemblages (*mélanges*); while the Ligurian sequence, generated by the subduction of the Tethyan Ocean, is represented mainly by Early Cretaceous-Early Tertiary chaotic deep water shaly rocks (*mélanges* and olistostromes) and by calcareous and arenaceous turbidite sandstones. The Ligurian thrust-nappe sequence overlies the Umbro-marchigiana-romagnola fold-and-thrust belt sequence. On the northern side of the chain, the Ligurian sequence is unconformably overlain by the Epiligurian sequence and by Neogenic and Quaternary terrigenous deposits. The Epiligurian sequence consists of a thick Paleocene-Early Messinian succession of matrix-supported breccias (olistostromes), deep water multi-color shales and marls, muddy and sandstone turbidites, conglomerates, shallow water siliciclastic and bioclastic deposits. The Neogene deposits consist mainly of marine deep water shales (Bettelli & De Nardo, 2001).

In this study site, the rocks affected by falling can be grouped as follows according to their geomechanical characteristics: a) stratified hard rocks (e.g., sandstones of Mt. Aquilone, San Marino Formation); b) alternations of strata with a relationship between hard and weak layers ≥ 3 (e.g., Poggio Carnaio Sandstones, Monte Morello Formation, various members of the Marnoso-arenacea romagnola Formation); c) alternations of strata with a relationship between hard and weak layers between 1/3 and 3 (e.g., Monte Senario Formation, pelitic-arenaceous and arenaceous-pelitic lithofacies of the Argille Azzurre Formation, various members of the Marnoso-arenacea romagnola Formation); d) conglomerates and slightly cemented breccias with clastic matrix (e.g., conglomerates of the Argille Azzurre Formation, conglomerates of the Colombacci Formation); e) sands and slightly cemented sandstones (e.g., arenaceous-organogenic lithofacies and Castrocaro lithofacies of the Argille Azzurre Formation); f) compact gypsum and gypsum with chaotic structure (e.g., Gessoso-Solfifera Formation and lithofacies of the Tetto Formation) (fig. 3).

Within those lithotypes, instability conditions of steep slopes mainly depend on the presence of abundant seeping water, besides the density and orientation of joints.

METHODOLOGY

The method applied for the identification of probable rock-fall runout areas has been derived from those proposed by various authors (Onofri & Candian, 1979; Heinimann & *alii*, 1998; Jaboyedoff & Labiouse, 2003; Piacentini, 2005) that consider energy dissipation proportional to maximum runout distance (fig. 4). As mentioned above, it

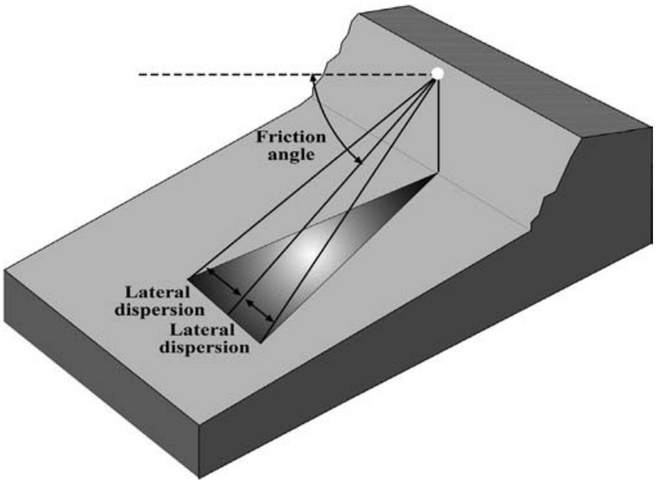

FIG. 4 - Outline of runout zones obtained through the three-dimensional empirical model.

is a three-dimensional empirical method. Referring to the simulation angles proposed by the cited authors, the probable fall trajectories have been assessed and, among those, the ones that could better suite the specific morphological features of the studied areas have been selected. In particular, the possible maximum runout zones have been calculated, using trajectories defined by angles, chosen from those suggested by Heinimann & *alii*, 1998 (tab. 1), variable with respect to the horizontal line from 33° to 90°. The simulations have been carried out considering the possible deviations of blocks from the fall profiles, assuming a probable lateral spread of falling blocks +/– 15° with respect to the dip direction.

These angles define three different zones of possible propagation with reference to block size and slope characteristics. In particular, blocks with a diameter less than 0.5 m can stop within all three zones. In the first one (zone 1), that is the closest to the detachment wall and defined by an equivalent friction angle of 37°, blocks can be stopped by trees, by a very irregular topography and by scree. The second zone (zone 2), the intermediate one, defined by an equivalent friction angle of 35°, can be reached by blocks when vegetation, topography and land-use conditions are less favourable than the ones cited beforehand. Finally, in the third zone (zone 3), the farthest and most conservative one, defined by angles of 33°, small blocks can propagate only under very unfavourable friction conditions. Blocks with diameters between 0,5 m and 2 m can instead reach zones 2 and 3 and stop there. Blocks stop in zone 2, the closest to the rock wall and bounded by an angle of 35° when high vegetation and irregular topography occur at the foot of the rock walls. Zone 3, the furthest one, is bounded by an angle of 33° and blocks stop here when land-use, vegetation and topography conditions do not allow the stop in zone 2.

TABLE 1 - Trajectories proposed by Heinimann & *alii* (1998)

Block dimension (diameter) < 0,5 m	0,5 - 2 m	> 2 m	Zone
Vegetation: meadow Topography: regular Soil: thin	Vegetation: bush Topography: slightly irregular Soil: thin	Vegetation: trees Topography: very irregular Soil: thick	33° ZONE 3
Vegetation: trees Topography: slightly irregular Soil: thick	Vegetation: trees Topography: very irregular Soil: thick		35° ZONE 2
Vegetation: trees Topography: very irregular Soil: scree			37° ZONE 1

For blocks with diameter over 2 m, only one possible stop zone can be identified, defined by an equivalent friction angle of 33° (zone 3).

The empirical model applied requires the availability of a digital elevation model (DEM), of geological information and of land-use maps and is based on semi-automatic procedures, for the identification of starting areas. Actually, the analysis of wide territories does not allow a detailed geomechanical survey. Therefore, the selection of potential starting zones is undertaken applying different criteria that use a cross validation between direct surveys and GIS functions. In particular, starting zones have been selected using morphological and lithological criteria and considering land use. From those starting areas, the different trajectories of blocks have been simulated using the «Viewshed» function (Spatial Analyst extension of ESRI® ARCGIS 8.3), given certain types of land-use, assessed dimensions of blocks and soil thickness. The model had to be accurately calibrated and input parameters had to be precisely determined. Those parameters were obtained after field surveys and back-analysis of past rock fall events. The empiric model has been purposely applied in areas with different geological and geomorphological characteristics in order to verify its applicability in different environmental contexts. The dolomitic environment is characterized by high energy of the relief and by rock types of coral-reef origin alternated by volcanic terrains. The Apennine environment is instead characterized by a smoother and more regular morphology and by the outcropping of mainly flysch and clayey rock types. The two selected study areas represent also two different climatic environments: the alpine one and the cold-temperate one. This has allowed to verify whether the method can be applied independently from the climatic conditions characterizing the territory that is being analysed.

APPLICATION OF THE METHODOLOGY TO THE DOLOMITES STUDY AREA

Lithology, slope angle and land-use classes that could be predisposing for rock falling have been selected in order to identify potential starting areas.

In particular, the outcropping rock types have been analysed on the basis of the specific geomechanical characteristics and of the degree of fracturing. These data have been derived from the «Map of macro-fracturing and of tectonic discontinuities» (Progetto CARG, Foglio 028 «La Marmolada», in progress) that shows all lineations identified for the whole study area through the interpretation of aerial photographs, digital ortho-photographs and satellite images. The most fractured formations are the dolomites and the limestones (Sciliar Dolomite, Cassian Dolomite, Dürrestein Dolomite, Dolomia Principale, Morbiac Limestones, Dachestein Limestones and Ammonitico Rosso), plus the Marne del Puez. The formations of Contrin, Livinallongo and Richthofen are fairly fractured, while the remaining lithotypes are scarcely fractured. Among all the outcropping formations, only those cited beforehand have been selected as potential source areas of rock falls.

The slope-angle value, assumed as critical for rock-fall initiation and derivable from a digital elevation model, has been selected on the basis of previous analyses undertaken within the Municipality of Corvara in Badia (Piacentini, 2006). In accordance with the values proposed by various authors, slope angles greater than 33° (Heinimann & *alii*, 1998), 40° and 45° have been selected. Comparing the obtained results with the rock walls that are potential source areas of rock falls, the criterion that best reproduces reality is the one that considers slopes with angles greater than 33°, in accordance with what has been proposed by Heinimann & *alii* (1998). This threshold is in fact conservative, without overestimating too much the potential source areas to be taken into account.

The input data regarding land-use classes have been divided, in order to be functional to the aim of the investigation, in typological classes showing the same behaviour towards rock falls. The selected classes have been the following ones: bushes, woods, talus and rocks.

By considering the different lithology, land-use and slope-angle classes, it has been possible to obtain different distributions of source areas. The obtained results have then been validated in the field, where potential source areas have been correctly identified considering slope angles greater than 33° and the specific land-use types (fig. 5). It has been possible to observe that, although with some overestimation, defined source areas and real critical areas match quite well. Therefore, the obtained potential starting areas represent a good starting basis for simulations of fall trajectories defined by angles chosen from those suggested by Heinimann & *alii* (1998) variable with respect to the horizontal line from 33° to 90° (fig. 6).

APPLICATION OF THE METHODOLOGY TO THE APENNINE STUDY AREA

The methodology previously applied in the Dolomites has been adopted also for the Apennine study area, after site calibration and verification. Specific lithology, land-use and slope-angle classes have been defined. For the definition of lithology classes, data from the Geological Map of the Emilia-Romagna Apennines (1:10,000 scale) and from the related lithotechnical map (Servizio Geologico, Sismico e dei Suoli, Regione Emilia-Romagna, 2006) have been used. The geological formations mostly affected by rock falls are those having stratified rock layers, alternations of strata with a relationship between hard and weak layers ≥ 3, alternations of strata with a relationship between hard and weak layers between 1/3 and 3, scarcely-cemented conglomerates and breccias, conglomerates and breccias with matrix, cemented sands and arenites, compact gypsums and gypsums with chaotic structure.

Regarding the slope-angle value considered as critical for rock fall initiation, different analyses have been per-

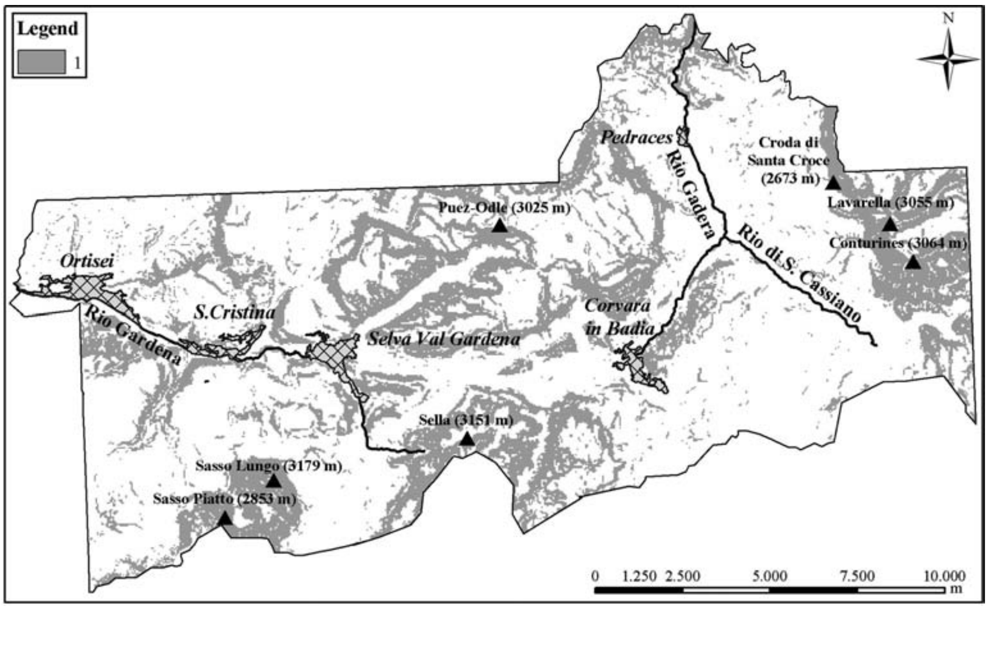

FIG. 5 - Map showing possible starting zones in the Dolomites. Legend: 1) Starting zones.

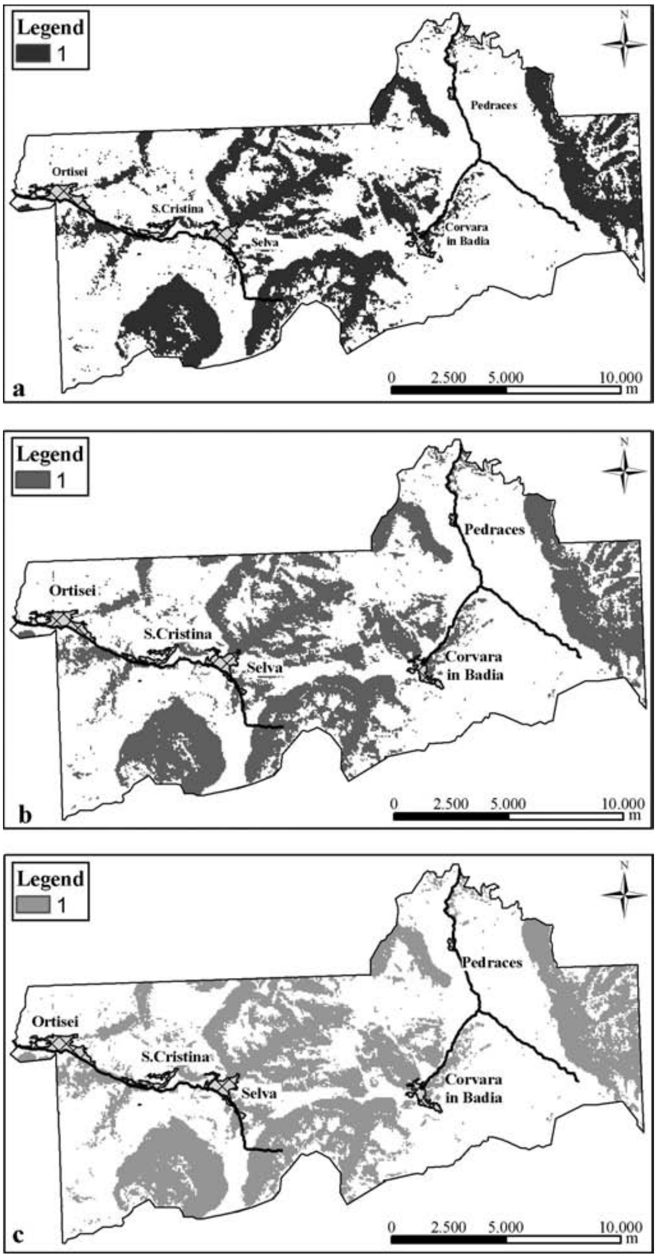

FIG. 6 - Map of possible runout zones in the Dolomites. Legend: a) zone 1; b) zone 2; c) zone 3.

formed to verify which is the minimum angle that best suits the examined territory. Various minimum angles have been examined (33°, 35°, 40° e 45°) and, on the basis of analyses undertaken with reference to selected test areas and of field checks, the slope angles that best reproduces real cases have values greater than 35°. This threshold is conservative, without overestimating too much the potential source areas to take into account.

Data on land-use have been derived from the Land-use Map of the Regione Emilia-Romagna (Servizi Informativi Geografici, Regione Emilia-Romagna, 1999), for the part of study areas laying within that Region, and from the Land-use Corine Map (European Environmental Agency, 2002), for the part of study areas laying within the Toscana Region. The different types of land use have been grouped into simplified classes on the basis of their potential to initiate rock falls. Eight classes have thus been identified (1. anthropic; 2. woods; 3. quarries and dumps; 4. bushes, 5. rivers, lakes and swamps; 6. orchards, olive-grooves and vineyards; 7. rock; 8. soil fit-for-seed, agricultural areas and meadows). Among these classes, only those where rock falls may occur have been selected, i.e., woods, bushes and rock. The rest have been excluded. Different distributions of starting areas have been obtained considering the various lithologies, land-use data and slope angles greater than 35°. Similarly to what has been done in the Dolomites, the output of the model has been verified by means of field survey (fig. 7), which showed a good reliability of the model results with respect to the identification of real starting areas.

From these starting zones, the possible maximum runout zones have been calculated, using trajectories defined by angles chosen from those suggested by Heinimann & *alii* (1998) variable with respect to the horizontal line from 33° to 90° (fig. 8).

RESULTS

The application of the same empirical method in two areas characterised by different geological and morpho-climatic conditions has allowed to verify its applicability and reliability. Field checks have, in fact, demonstrated that the method has given sound results in identifying probable rock-fall runout zones both in the Apennines and in the Dolomites. The obtained results have then been validated using kinematic methods. The application of the empirical model has allowed to identify three possible runout scenarios on the basis of the rock-fall mass involved. Blocks with diameters less than 0.5 m can in fact stop within three zones (zone 1: with 37° slope angle, zone 2: with slope angles between 35° and 37°, zone 3: with slope angles between 33° and 35°) as a function of other variables such as, for instance, the morphology of the slope where blocks fall on and the presence of vegetation. Blocks with medium diameter between 0.5 and 2 m can instead stop within two zones (zone 2: with 35° slope angle, zone 3: with slope angles between 33° and 35°), again as a function of the conditions of the slope below. Finally, blocks with diameter greater than 2 m can be distributed within only one zone (zone 3: with 33° slope angle).

The simulation of possible runout should therefore take into account, for blocks with medium-small dimensions, the boundary conditions represented by the type of vegetation at the foot of the slope, the thickness of the material affected by the rock fall and the topography.

It should be noticed that the results don't consider the presence of mitigation works and of anthropic elements, which may be considered in a further step of the investigations, in order to assess how they can influence the runout.

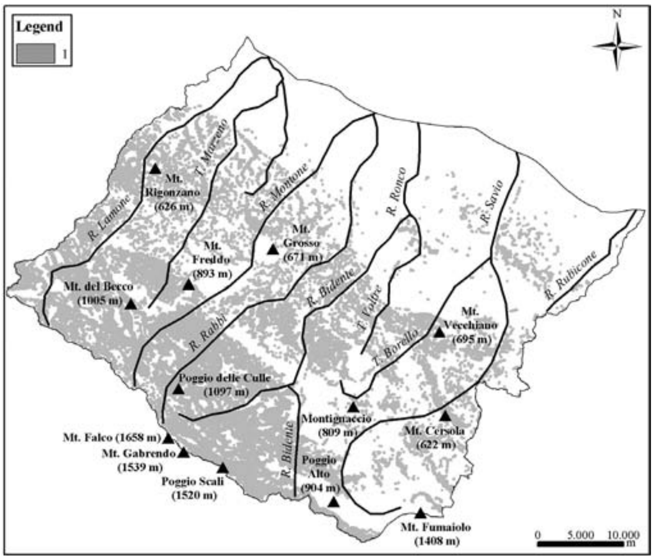

FIG. 7 - Map showing possible starting zones in the northern Apennines. Legend: 1) Starting zones.

CONCLUSIONS

The research has shown that a small-scale assessment (1:25,000) of rock-fall possible runout zones, independent from detailed geomechanical surveys and from the assessment of kinematic rupture, can be satisfactorily carried out by means of an empirical model. The empirical model used proved to be suitable and cost-effective for investigations over wide territories. Although it does not mathematically predict the motion of fall, it can adequately assess possible rock-fall runout. It should be noticed that the model, on the one hand, has the advantage to require few input data that generally can be easily found (DEM, geology and land-use) but, on the other hand, is greatly influenced by the resolution and quality of these data.

Anyhow, the research has demonstrated that, after a careful calibration and verification phase, it is possible to quickly and efficiently undertake analyses that are sufficiently accurate, also for wide areas.

The reproducibility of the method is guaranteed by the easy acquisition of input data. The criteria used to select potential starting points for rock falls can be used also in areas where detailed geological surveys do not exist and where there is no information regarding the degree of fracturing of rock masses.

Analyses made with this kind of empirical model enable the acquisition of reliable information regarding potentially hazardous areas where detailed surveys should be then carried out. Areas of potential runout of blocks can be furthermore analysed in relation to elements at risk like buildings, roads etc. This can allow to highlight the actual distribution of high-risk areas and to point out which rock cliffs should be studied in detail and where sectors mitigation measures are needed.

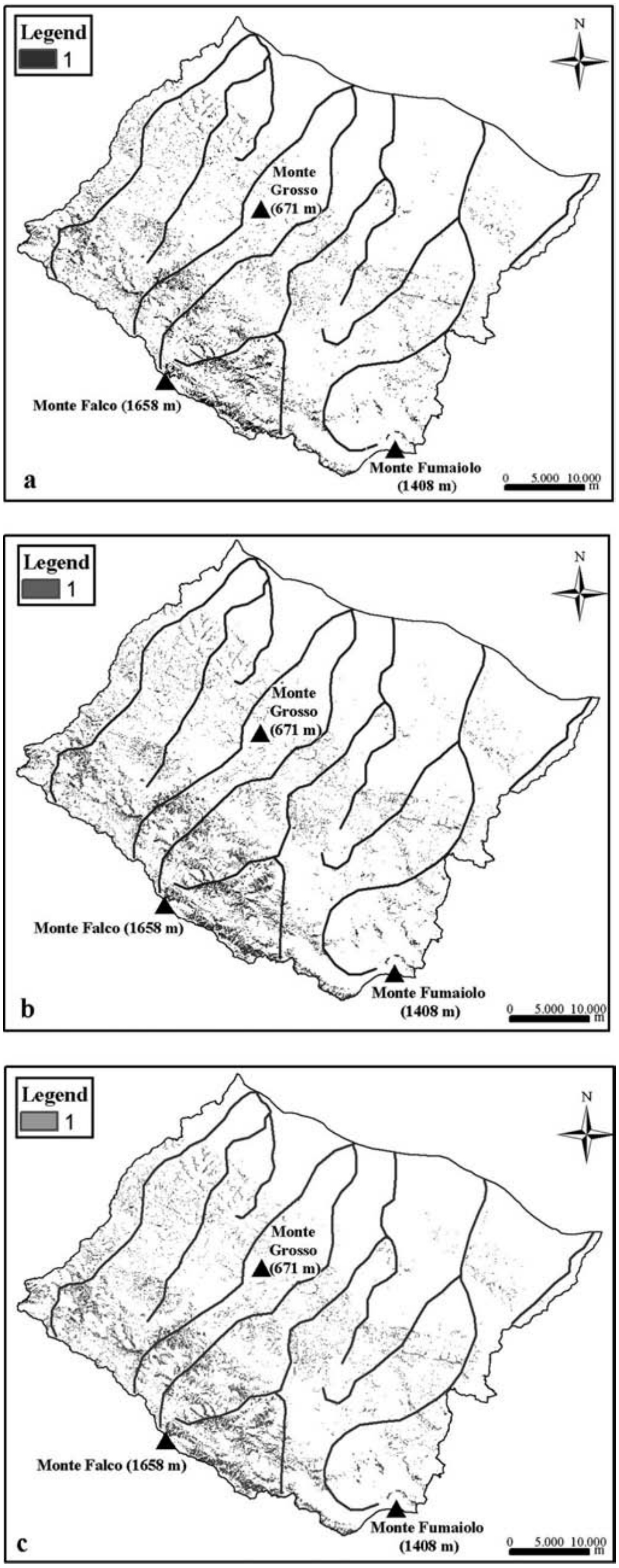

FIG. 8 - Map of possible runout zones in the northern Apennines. Legend: a) zone 1; b) zone 2; c) zone 3.

Finally, the research has showed that the methodology tested in the Dolomites and in the northern Apennines can be applicable also in other geological and morphoclimatic contexts, including costal cliffs where the method is presently under testing by the authors.

REFERENCES

AGLIARDI F. & CROSTA G.B. (2003) - *High resolution three-dimensional numerical modelling of rockfalls.* International Journal of Rock Mechanics and Mining Sciences, 40, 455-471.

AZZONI A., LA BARBERA G. & ZANINETTI A. (1995) - *Analysis and prediction of rockfalls using a mathematical model*. International Journal of Rock Mechanics and Mining Sciences Geomechanics Abstracts, 32(7), 709-724.

BETTELLI G. & DE NARDO M.T. (2001) - *Geological outlines of Emilia Apennines (Italy) and introduction to the rock units cropping out in the areas of landslides reactivated in the 1994-1999 period*. Quaderni di Geologia Applicata, 8(1), 1-26.

COCCO S. (1991) - *Frane di crollo, definizione dei coefficienti di dissipazione dell'energia*. Studi Trentini di Scienze Naturali, Acta Geologica, 68(2), 3-30.

CROSTA G.B., CARRARA AGLIARDI F., CAMPEDEL P. & FRATTINI P. (2006) - *Valutazione della pericolosità da caduta massi tramite un approccio integrato statistico e deterministico*. Giornale Geologia Applicata, 4, 41-48.

DEL MASCHIO L., PIZZIOLO M., GOZZA G. & PIACENTINI D. (2004) - *Una metodologia integrata in ambiente GIS per l'analisi dei fenomeni di crollo: il caso studio di Monte delle Formiche (BO).* Il Geologo dell'Emilia-Romagna, Anno IV, 19, 43-51.

DEL MASCHIO L., GOZZA G., PIACENTINI D., PIZZIOLO M., & SOLDATI M. (2007) - *Previsione delle traiettorie di blocchi mobilizzati da frane di crollo: applicazione e confronto di modelli*. Giornale di Geologia Applicata, 6, 33-44.

GEO&SOFT (2004) - *Rotomap, Manuale d'uso*. www.geo&soft.it

EUROPEAN ENVIRONMENTAL AGENCY (2002) - *CORINE land cover update. I&CLC2000 project.* European Environmental Agency.

GUZZETTI F., CROSTA G., DETTI R. & AGLIARDI F. (2002) - *STONE: a computer program for the three-dimensional simulation of rock-falls*. Computers and geosciences, 28, 1079-1093.

HEINIMANN H.R., HOLTENSTEIN K., KIENHOLZ H., KRUMMENHACHER B. & MANI P. (1998) - *Methoden zur Analyse und Bewertung von Naturgefahren*. Umwelt-Materialien Nr. 85, Naturgefahren, BUWAL, Bern, 248 pp.

JABOYEDOFF M. & LABIOUSE V. (2003) - *Preliminary assessment of rockfall hazard based on GIS data*. ISRM 2003, Technology roadmap for rock mechanics. South Africa Institute of Mining and Metallurgy, 1, 575-578.

ONOFRI R. & CANDIAN C. (1979) - *Indagine sui limiti di massima invasione dei blocchi rocciosi franati durante il sisma del Friuli del 1976*. Regione Autonoma Friuli Venezia Giulia, CLUET, 42 pp.

PARONUZZI P. & ARTINI E. (1999) - *Un nuovo programma in ambiente Windows per la modellizzazione della caduta massi*. Geologia tecnica e ambientale, 1, 13-24.

PIACENTINI D. (2005) - *Studio preliminare per l'analisi della stabilità di pareti rocciose: un esempio di applicazione nelle Dolomiti Occidentali (Provincia di Bolzano, Italia).* HydroGeo, 0, 50-55.

PIACENTINI D. (2006) - *Metodi innovativi per la valutazione della pericolosità da frana, con particolare attenzione ai fenomeni di crollo di roccia: casi studio nelle Dolomiti e nell'Appennino Emiliano*. Tesi di Dottorato. Università degli Studi di Modena e Reggio Emilia, Dipartimento di Scienze della Terra, 322 pp.

PROGETTO CARG (in progress) - *Foglio 028 «La Marmolada»*. Provincia Autonoma di Bolzano.

SERVIZI INFORMATIVI GEOGRAFICI, REGIONE EMILIA-ROMAGNA (1999) - *Carta dell'Uso del Suolo, scala 1:25.000*. http://www.regione.emilia-romagna.it

SERVIZIO GEOLOGICO, SISMICO E DEI SUOLI, REGIONE EMILIA-ROMAGNA (2006) - *Carta Geologica dell'Appennino Emiliano-Romagnolo, scala 1:10.000*. http://www.regione.emilia-romagna.it

(Ms. presented 28 April 2007; accepted 30 August 2008)