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EVALUATION OF SLIDING SUSCEPTIBILITY IN VOLCANICLASTIC SOILS OF CAMPANIA (SOUTHERN ITALY) AIDED BY GIS TECHNIQUES

ABSTRACT: PERRIELLO ZAMPELLI S., *Evaluation of sliding susceptibility in volcaniclastic soils of Campania (Southern Italy) aided by GIS Techniques*. (IT ISSN 0391-9838, 2009).

A method for evaluating the susceptibility to debris slides, due to critical rainfall sequences, is discussed. The method concerns the volcaniclastic soils of Campania (Southern Italy) covering carbonatic slopes. It is based on the concept that, for a spatially homogeneous soil cover and a spatially homogeneous triggering rainfall sequence, different values of threshold slope gradient exist for limit equilibrium conditions, depending on the continuity and planform curvature of the soil cover. The method derives from the analysis of the location of the source areas of the landslides originated on May 5, 1998, on the slopes of the Pizzo d'Alvano massif, when more than a hundred of almost contemporary debris slides were triggered, providing a consistent data set.

In order to test the potential of the method for the spatial prediction of debris slide triggering also in other areas of Campania displaying similar geomorphology and soil cover, it has first been applied to that same massif to verify, although *a posteriori*, its ability to assess the sliding susceptibility of the volcaniclastic soils prior to the May 1998 event. Comparison of the sliding susceptibility resulting from the method and the locations of the actual May 5, 1998, landslide source areas provided good results: the susceptible areas, covering 15% of the studied area, overestimated the actual source areas, while 94% of the actual source areas fell into susceptible areas. Accordingly, a simplified version of the method has been applied to a much larger area, historically and also recently struck by debris slides - debris avalanches - debris flows. Although, in this latter case, a comparison of the resulting sliding susceptibility with the locations of actual landslide source areas could be carried out only for a limited number of recent events, the results have provided useful hints for analysing the risk associated to this type of landslides in Campania.

While it has originally been developed with regard to the volcaniclastic soil covers of Campania, where the role of discontinuities is generally deemed as particularly relevant to the spatial distribution of the source areas of debris slides, the method discussed in the present paper could profitably be used (with suitable adaptation and calibration) for assessing the rainfall-triggered shallow landsliding susceptibility also in different, residual and/or colluvial soil, contexts.

KEY WORDS: Debris-slide susceptibility, Volcaniclastic soil cover, Soil cover discontinuities, Ground curvature, Campania (Italy).

RIASSUNTO: PERRIELLO ZAMPELLI S., *Valutazione della suscettibilità allo scivolamento dei suoli vulcanoclastici campani con l'ausilio di tecniche GIS*. (IT ISSN 0391-9838, 2009).

Nel presente lavoro viene discusso un metodo di valutazione della suscettibilità nei confronti di *debris slides* dovuti a precipitazioni critiche. Il metodo riguarda i suoli vulcanoclastici della Campania a copertura di versanti carbonatici. Esso è basato sul concetto che esistono, per una copertura di suolo spazialmente omogenea e per una sequenza di pioggia scatenante spazialmente omogenea, differenti valori soglia di pendenza per il raggiungimento di condizioni di equilibrio limite, dipendenti dalla continuità e dalla curvatura del pendio in direzione ortogonale alla massima pendenza. Il metodo deriva dall'analisi delle aree d'innesco delle frane del 5 maggio 1998 sul Pizzo d'Alvano, quando più di cento *debris slides* furono innescati quasi contemporaneamente, fornendo quindi un significativo set di dati.

Per poter sperimentare il potenziale del metodo verso la predizione spaziale dell'innesco di *debris slides* anche in altre aree della Campania che mostrano caratteristiche geomorfologiche e copertura di suolo simili, esso è stato applicato allo stesso rilievo per verificare, sebbene a posteriori, la sua capacità di determinare la suscettibilità allo scivolamento dei suoli vulcanoclastici nelle condizioni precedenti al maggio 1998. La comparazione della suscettibilità allo scivolamento ottenuta attraverso il metodo e le posizioni delle aree di scivolamento iniziale delle frane del 5 maggio 1998 ha fornito buoni risultati: le aree considerate suscettibili, che coprono il 15% dell'area oggetto di studio, hanno sovrastimato l'estensione delle reali aree di scivolamento iniziale, ma allo stesso tempo il 94% di queste è risultato ricadere in aree considerate suscettibili. Conseguentemente, una versione semplificata del metodo è stata applicata ad un'area molto più vasta, sia storicamente che recentemente interessata da *debris slides - debris avalanches - debris flows*. Nonostante il fatto che l'estensione dell'area considerata abbia permesso la comparazione della suscettibilità risultata con le aree d'innesco di frane solo per un limitato nu-

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mero di frane recenti e perciò affidabilmente localizzate, i relativi risultati permettono utili riflessioni nel contesto dell'analisi del rischio connesso a questo tipo di frane in Campania.

Sebbene il metodo qui discusso sia stato sviluppato relativamente alle coperture di suoli vulcanoclastici campane, nelle quali il ruolo delle discontinuità viene generalmente considerato particolarmente rilevante nei confronti della distribuzione spaziale delle aree d'origine dei *debris slides*, esso potrebbe convenientemente essere utilizzato (con gli opportuni adattamenti e calibrazione) nella valutazione della suscettibilità allo scivolamento innescato da precipitazioni anche in altri contesti, relativi per esempio a coperture residuali e/o colluviali.

TERMINI CHIAVE: Suscettibilità a *debris slides*, Copertura di suoli vulcanoclastici, Discontinuità nella copertura di suolo, Curvatura della superficie.

INTRODUCTION

The prediction of the occurrence of complex, debris slide, debris avalanche, debris flow landslides (Cruden & Varnes, 1996; Hungr & *alii*, 2001; Jakob & Hungr, 2005), that are frequent on slopes covered by soils constituted by layers of variously altered volcaniclastic sediments (herein referred to as volcaniclastic soils), which cover a significant part (cf. 1 in fig. 1) of Campania, (Southern Italy, see: Rolandi & *alii*, 1998, 2000; Terribile, 2000; De Vita & *alii*, 2006), represents a difficult challenge.

Every time a new landslide of this type occurs, often causing victims and/or damage, the question of its *a priori* predictability arises, although at different levels of awareness.

From a scientific point of view, such a question must be separated into at least three factors, that indeed constitute the hazard (Varnes, 1984) related to such landslides. Generally speaking, the factors that determine landslide hazard are:

– a time factor (when the landslide will occur?);
– an intensity factor (how «big» the landslide will be?);
– a spatial factor (where the landslide will occur?).

Limiting the analysis to rain-induced landslides, the time factor is related to the time of occurrence of a «critical» rainfall intensity/duration sequence over a given slope covered by a thickness of soil. Among the mechanisms that were hypothesized for rainfall-triggered debris slides, starting from Celico & *alii* (1986) for Campania, there are nowadays experimental evidences relative (i) to the complex pattern of pore pressure distributions within soil covers and underlying bedrock (for northwestern U.S.A., see: Torres & *alii*, 1998; Montgomery & *alii*, 2002), and (ii) to limit equilibrium conditions which may locally occur within steeply inclined, unsaturated volcaniclastic soils, when subsurface flow induced by the rain makes the degree of saturation and the unit weight increase, and the suction-related apparent cohesion diminish, until shear strength equals shear stress and landslides are triggered (for Campania, see: Olivares & Picarelli, 2001, 2003; Bilotta & *alii*, 2005).

The intensity factor is assumed as constant here, as (i) most of the past complex landslides with source areas within volcaniclastic soils covering carbonatic slopes displayed comparable intensities, and (ii) intensity of this type of landslides is related essentially to factors, not discussed here, controlling their capability of mobilizing and incorporating other materials below the source areas, and thus their transformation into debris avalanches and/or debris flows.

The spatial factor is certainly related to triggering rainfall sequences, in terms of their areal distribution, but also to characters of the soil cover and of the slopes, among which are overall soil shear strength, slope angle, and slope morphology. Recent researches (Mazzarella & De Luise, 2007) and weather radar data (Casagli N., personal communication) showed that critical, landslide-triggering rainfall sequences can indeed be concentrated over very limited areas, as in the case of the April 2006 Ischia (Campania) landslides. On the other hand, the part of Campa-

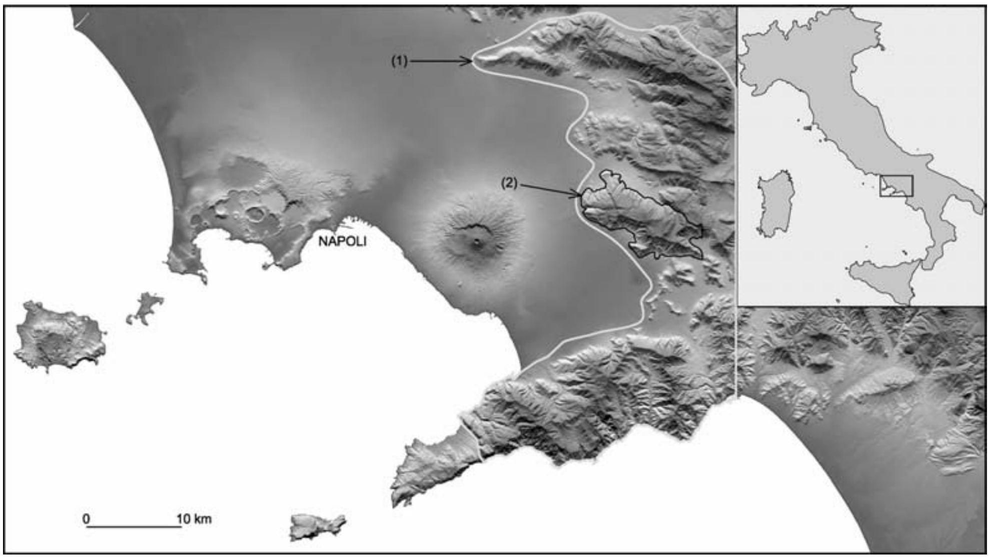


FIG. 1 - Overview of the studied area. Key: 1) perimeter of the studied area; 2) Pizzo d'Alvano massif (see also figs. 5 through 7).

nia affected in the past by landslides within volcaniclastic soils covering carbonatic bedrock is rather large (part of it is in fig. 1). Unfortunately, real-time monitoring of rainfall by means of weather radar has not yet been implemented in Campania. Perspectively, such a monitoring could provide the necessary data for localized and timely alerts (Crosta & Frattini, 2003). Therefore, an objective identification of the areas where such types of landslides are likely to originate (i.e. an assessment of the debris-slide susceptibility: Soeters & Van Westen, 1996; Dai & *alii*, 2002) in case of triggering rainfalls sounds useful. In fact, while debris slides pose a relatively small risk at the source locations (sites of initial failure), the related debris avalanches (Hungr & *alii*, 2001; Guadagno & *alii*, 2005) and/or the debris flows that usually originate from them by liquefaction can constitute a serious threat to people and structures along their paths, especially when they become channelled (Di Crescenzo & Santo, 2005) and travel long distances, thanks to the incorporation of water and sediments from the channels.

If sliding susceptibility could be assessed reliably, estimates of the potential debris avalanche/flow paths and run-out (see: Revellino & *alii*, 2004; Revellino & *alii*, 2008; Iovine, 2008), together with analyses of the vulnerability and of the exposed values at the foot of slopes, could provide useful elements for the inclusion of targeted soil stabilization on the slopes in evaluations of hazard and risk reduction options.

On a regional scale, debris slide susceptibility maps can be constructed using elevation data and a variety of techniques ranging from simple correlations, to use of expert judgment, and to process-based modelling. The success of these approaches depends strongly on the quality of the topographic data (Dietrich & Sitar, 1997).

THE SL.I.DE. METHOD

In the following, a method for the identification of volcaniclastic soil-covered slope areas that are susceptible to debris slides in Campania is discussed. The method is not based on numerical modelling of the processes of rainfall, infiltration, unsaturated flow, pore pressure increase and shear strength decrease in a continuous (while not necessarily homogeneous) soil cover (process-based models: see, among others, Montgomery & Dietrich, 1994; Dietrich & Sitar, 1997; Iverson, 2000; Crosta & Frattini, 2003; Frattini & *alii*, 2004), as:

- the interested area is too large;
- the majority of past events in the study area originated very close to discontinuities within the soil cover (Guadagno, 2000; Guadagno & Perriello Zampelli, 2000; Crosta & Dal Negro, 2003; Di Crescenzo & Santo, 2005; Guadagno & *alii*, 2005; Perriello Zampelli, 2007), indicating a significant role for discontinuities in reaching limit equilibrium conditions, and thus making such infinite slope-based models inapplicable.

Recent numerical modelling analyses (Basile & *alii*, 2003; Crosta & Dal Negro, 2003; Guadagno & *alii*, 2003; Mele & *alii*, 2007) investigated the role of discontinuities in the flow patterns, pore pressure distribution and (only Crosta & Dal Negro, 2003, and Guadagno & *alii*, 2003) equilibrium conditions in model volcaniclastic soils. Notwithstanding the different methods employed, the results obtained by these Authors explained the concentration of debris-slide sources close to discontinuities in the soil cover.

Due to the unfeasibility of considering discontinuities in process-based models, a method based on simple geo-morphological considerations was devised (Perriello Zampelli, 2007; Iovino & Perriello Zampelli, 2007), and is developed further here. Such considerations, assuming spatially homogeneous triggering rainfall and soil cover, are:

- debris slides are likely to occur on soil-covered slopes above a certain gradient threshold;
- threshold slope gradient is lower near discontinuities and in hollows of the soil cover (all other controlling factors considered constant), with respect to planar, continuous slopes (referable to as infinite slopes).

Therefore, the method is based on the assessment of:

- the presence (and, possibly, the type and thickness) of volcaniclastic soil on the slopes;
- the presence of discontinuities in the soil cover;
- slope gradients and curvatures, by means of good resolution Digital Terrain Models.

The method, intended as a practical engineering-geological tool, was named SL.I.DE. (from SLide Initiation areas Detection, see: www.progettoslide.unina.it). It derives from the observation of the morphological characters of the source areas of the main complex debris slides - debris flows (cf. 2 in fig. 1) triggered on May 5, 1998 at Pizzo d'Alvano (Guadagno & Perriello Zampelli, 2000; Perriello Zampelli, 2007). More than 60% of the sample of 145 sources considered in this area originated within 10 metres from a soil cover discontinuity (either road/track cuts or bedrock outcrops), at slope inclinations generally lower than those observed for slides within continuous soil covers (Perriello Zampelli, 2007).

Compared to other similar landslides recently occurred in Campania, the May 1998 landslides at Pizzo d'Alvano are particular, due to their abundance and spatial density, and for their near-simultaneity.

These characters allowed for some simplifying assumptions:

(i) the triggering rainfall sequence was considered spatially homogeneous for all considered landslides;

(ii) the volcaniclastic soil cover was considered spatially homogeneous for all source locations;

(iii) the location of the sources was primarily controlled by the value of the slope angle, provided that different slope threshold angles are considered, depending on soil cover continuity and curvature (fig. 2).

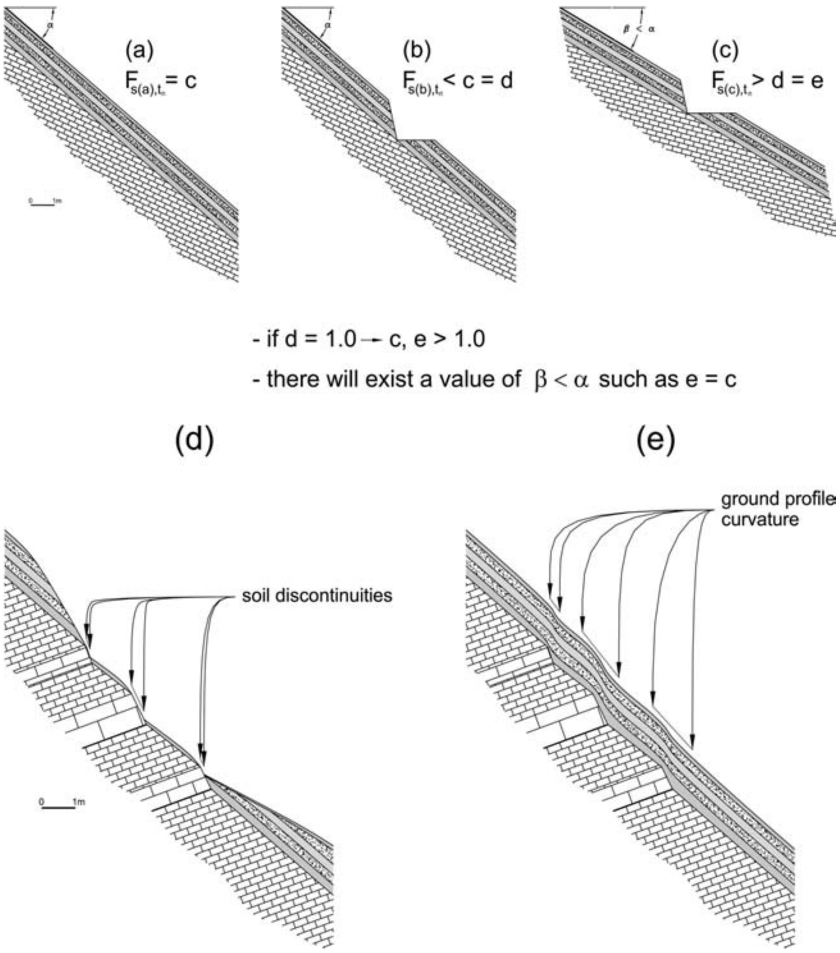


FIG. 2 - Types of slopes. Key: a) infinite slope; b), c), d) finite slopes with one or more discontinuities in the soil cover; e) continuous, non-homogeneous, curved soil cover.

In other words, rainfall, as well as nature, thickness and shear strength of the soil, while obvious primary controlling factors of failure, were simply considered as spatially constant (as is also often assumed when using process-based models, e.g. in Frattini & *alii*, 2004) throughout the study area, in order to focus on the latter hypothesis. This implies that, all other controlling factors being considered as constant, different values of slope angle are needed for limiting equilibrium conditions (fig. 2), when:

a) the slope is sufficiently planar that it can be analyzed as an infinite slope, with a continuous soil cover of constant thickness;
b) the slope, displaying discontinuities and/or non-homogeneous soil cover and gradients, has to be analyzed as a finite slope.

In its first version (revision 0), the SL.I.DE. method (Perriello Zampelli, 2007) was applied to the Pizzo d'Alvano study area as it was before the May 1998 event, to test its ability to detect, and therefore potentially predict, the areas where the landslides actually took place afterwards. Based on the screening of source areas of the May 5, 1998, landslides in terms of location and inclination, two sliding susceptibility categories were implemented:

1) areas covered by volcaniclastic soils, with slope angle ≥ 40°;
2) areas within 10 m of either bedrock outcrops or centreline of roads and tracks, covered by volcaniclastic soils, with slope angle ≥ 30°.

The choice of the above slope angle parameters derived from a trial-and-error process, aimed at obtaining the best correspondence among actual May 1998 source areas and susceptible areas, as delineated by the SL.I.DE. revision 0 method. Statistically meaningful validation (Baeza & Corominas, 2001; Chung & Fabbri, 2003) of the method and of the chosen parameters was not attempted.

At revision 0, with the above-mentioned slope threshold angle values, the method overestimated the extent of susceptible areas with respect to the debris slides which were actually triggered in May 1998. The logic of the method allowed for an area to be considered as susceptible to sliding when it satisfied either one of, or both, the above conditions. Therefore the total area considered susceptible to sliding results from the Boolean union of the areas belonging to the two categories. The percentage of areas classified as susceptible to sliding, with respect to the total investigated area, resulted 12%. When limiting the investigated area to the sum of its parts with slope angle ≥ 25°, the percentage was 18%. 78% of the 145 considered landslide source areas fell within the union of the two susceptibility categories: when considering only the landslides that occurred within 10 m of soil cover discontinuities, 97% of them fell within the second category of susceptible areas (whose percentage with respect to the total investigated area was 7%). However, it was observed that the majority of the cut-and-fill tracks, present on slopes dipping 30° or more, did indeed reach limit equilibrium conditions on May 5, 1998 (fig. 3), although in many cases the failure processes apparently did not cause displacements large enough for the involved soils to liquefy. A complete survey of the debris slides along cut-and-fill tracks that did not evolve to debris avalanches and/or flows was however not performed, so it was not possible to quantify an overestimation rate. Nevertheless, such overestimation lies on the safe side, in terms of a hypothetical *a priori* spatial prediction of soil sliding susceptibility in the studied area (fig. 1).

FIG. 3 - Example of a non-catastrophic failure along a discontinuity in the soil cover.

It is interesting to stress that, at Pizzo d'Alvano, a significant percentage (16%) of the May 1998 debris slides originated close to trackways that are not anymore visible (Perriello Zampelli, 2007). This fact points out the importance of field surveys and aerial photographs right after the event, as well as of careful analyses of old topographic maps and aerial photographs, aimed at recognizing soil cover discontinuities.

By considering that the original method did not perform sufficiently well on slope areas not affected by soil discontinuities, Iovino & Perriello Zampelli (2007) proposed a revision (revision 1) of the same method. Due to the curvature (second derivative of the slope angle) of the ground surface, a third category of slope areas susceptible to soil sliding, which cannot be analyzed by means of infinite slope schemes, was implemented, in terms of:

3) areas covered by volcaniclastic soils, with slope angle ≥ 35° and overall ground curvature ≥ 0,021.

In this way, both convexities and concavities could be detected, although not distinguished: convexities can pinpoint also a thinning of the soil cover (with possible truncation of some of its layers), while concavities enclose also the «hollows» detailed by Ellen (1988), and first indirectly recognized in the process-based model by Montgomery & Dietrich (1994). Such hollows represent the places where limit equilibrium conditions are first reached in case of critical rainfall/infiltration sequences in continuous soil covers as, even assuming a constant thickness of the soil cover, they represent the sites of convergence of both surface and subsurface flow lines, allowing for a faster increase in water content and pressure.

In the present paper, a further revision (revision 2) of the SL.I.DE. method is described, based on analysis of ground surface curvature in ArcGIS (ESRI). In particular, the parameterization of the planform curvature (Zeverbergen & Thorne, 1987; Moore & *alii*, 1991) allowed for the detection of slope areas that are concave upwards in transverse sections, or hollows.

In the revision 2 of the method, three categories of sliding susceptibility are considered:

1) areas covered by volcaniclastic soils, with slope angle ≥ 45°;
2) areas within 10 m of either bedrock outcrops or centre-line of roads and tracks, covered by volcaniclastic soils, with slope angle ≥ 30°;
3) areas covered by volcaniclastic soils, with slope angle ≥ 35°, and ground planform concavity ≥ 0,1.

The choice of the above parameters once again derives from a trial-and-error process, aimed at obtaining the best correspondence among actual May 1998 source areas and susceptible areas predicted by the SL.I.DE. method.

As in previous releases, the method relies on the representativeness and accuracy of digital terrain models (DTMs). For this reason a new DTM, based on the recent official 1:5.000 3D digital cartography of the Campania region, was used.

The first step towards the construction of the DTMs was the extraction from such cartography of all the points and vertices describing objects lying on the ground surface. The second step was the construction of the DTMs, both in vector and raster form, with a 5x5 m grid interpolation, with no imposed break lines and therefore continuous curvature. For the vector DTMs, the Quicksurf (Schreiber Instruments) software was used, while for the raster DTMs the ArcGIS (ESRI) Topo to Raster tool. The reason for using both forms of DTMs lies in the choice of using vector overlaying operations: as the ground planform curvature could be obtained only by means of raster analysis, its results were converted to vector form. The third step consisted in a careful survey of all the rock outcrops and detectable discontinuities in the volcaniclastic soil cover, by means of interpretation of orthophotos, of 1:5,000 topographic maps (including the late 70's Cassa per il Mezzogiorno «Carta Tecnica Regionale» of Southern Italy, representing until 2004 the only detailed topographic map available for the area) and direct surveying. The fourth step, finally, consisted of the implementation of a GIS platform for data analyses.

RESULTS

TEST AREA: PIZZO D'ALVANO

The SL.I.DE. (revision 2) method was applied again to the Pizzo d'Alvano study area, to test its effectiveness with respect to the May 1998 landslides. The results are entirely new with respect to those already published in Perriello Zampelli (2007), being derived from the recent Campania Region digital 1:5.000 topographic map.

Slope areas were deemed as susceptible to sliding when satisfying one or more of the three above-mentioned criteria (due to the logic of such criteria areas can, and some actually do, satisfy more than one criterion). Here, too, statistically meaningful validation (Baeza & Corominas, 2001; Chung & Fabbri, 2003) of the method and of the chosen parameters was not attempted.

With respect to the first release of the method, the percentage of the May 1998 source areas that were classified into at least one of the three categories rose from 78% to 94%, despite an increase of 5° in the slope angle threshold of the first category. This can be explained by considering (i) the greater accuracy of the new DTM, but also (ii) the third category, consisting of slope hollows covered by volcaniclastic soil cover and with slope angles of at least 35°.

Tab. 1 and fig. 4 show a synthesis of the results. In tab. 1, it should be noted that some source areas fall within more than one single susceptibility category: therefore the percentages must be considered separately.

In figure 4 it can be noted how the method, at revision 2, still overestimates the areas susceptible to debris sliding, with respect to the actual source areas of the May 1998 landslides. 15% of the 60 km^2 study area is considered as susceptible to sliding: considering only the portion of the

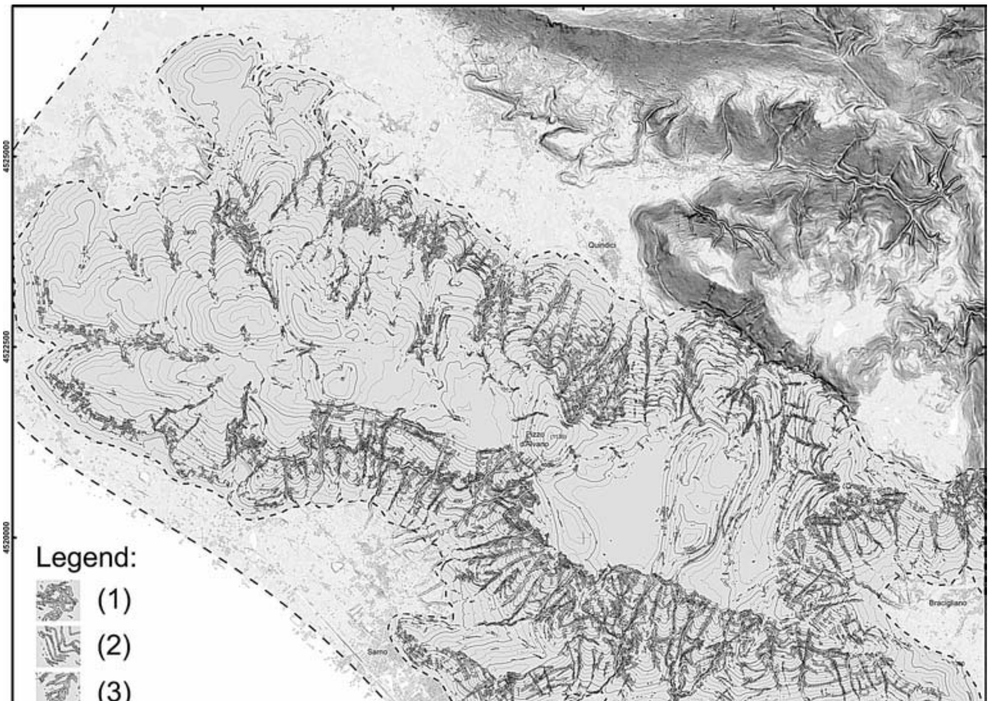


FIG. 4 - Debris-slide susceptibility map (Gauss-Boaga, Rome 1940 datum) of the Pizzo d'Alvano area (see fig. 1), as obtained by applying the SL.I.DE. revision 2 method. Key: 1) first category of susceptibility: areas covered by volcaniclastic soils, and slope angles ≥ 45°; 2) second category of susceptibility: areas within 10 m of bedrock outcrops or of the centreline of roads and tracks, covered by volcaniclastic soils, and slope angles ≥ 30°; 3) third category of susceptibility: areas covered by volcaniclastic soils, slope angles ≥ 35°, and ground planform concavity ≥ 0,1; 4) outlines of the May 1998 landslides. A digital version in color is available online at: http://www.progettoslide.unina.it/GeoIt2007/tiff/fig4.zip.

TABLE 1 - Synthesis of the results obtained with the SL.I.DE. (revision 2) method at Pizzo d'Alvano (May 1998 landslides)

Sector	**Source areas**	**# of source areas falling in Cat. (1)**	**%**	**# of source areas falling in Cat. (2)**	**%**	**# of source areas falling in Cat. (3)**	**%**	**# of source areas not falling in any Category**	**%**
Quindici	59	11	18,6	38	64,4	33	55,9	8	13,6
Sarno	56	28	50,0	38	67,9	45	80,4	0	0,0
Siano	11	4	36,4	7	63,6	10	90,9	0	0,0
Bracigliano	19	7	36,8	8	42,1	15	78,9	1	5,3
Total	145	50	34,5	91	62,8	103	71,0	9	6,2

study area with slope angle ≥ 25°, the percentage of areas susceptible to sliding amounts to 25%.

Overestimation can be explained, as noted above, by considering that even though many slope areas (especially those interested by cut-and-fill tracks) did indeed reach limit equilibrium conditions on May 1998, displacements were apparently not always large enough for liquefaction, thus for transition to debris avalanches and/or flows, to occur. However, such overestimation lies on the safe side in terms of spatial prediction.

Together with overestimation, absence of landslides in areas classified as susceptible to sliding remarks the fact that the assumptions of spatially homogeneous rainfall and, in particular, volcaniclastic soil cover are, as obvious, overly simplified. Should criteria, techniques (e.g. in De Vita & *alii*, 2006), and data regarding soil cover areal differentiation with respect to slope threshold angle values become widely available and meaningful, they could easily be implemented in the SL.I.DE. method.

Percentage of landslides in the Quindici sector is quite low in the third category: this can be explained by the dip-oriented attitude of the slopes on which the debris slides originated, which renders them more planar than in other cases. On the other hand, on such slopes the soil discontinuities are frequent and almost exclusively artificial, due to tracks built for forestry activities. Many of these tracks are not visible anymore, although they are clearly depicted on the older 1:5.000 topographic maps (Cassa per il Mezzogiorno, ca. 1980). In 16% of the cases, source areas of debris slides are found within 10 m of such tracks, and they could not be explained otherwise in 8% of the cases. Similar situations are likely to exist also in other similar slope areas in Campania, where forestry activities are equally traditional on the slopes.

A further aspect, related to the potential intensity of complex landslides that could develop from debris slides, concerns the relevance of the areas susceptible to debris sliding that are located on open, either planar or convex slopes. As observed in previous studies (Crosta & Dal Negro, 2003; Di Crescenzo & Santo, 2005; Guadagno & *alii*, 2005), debris slides originating from sources located on open slopes do not immediately evolve into debris flows («channelled» type landslides; Di Crescenzo & Santo, 2005) but, as in many of the May 1998 cases, they first evolve to debris avalanches, through a gravity driven wave-like propagation of the failure-liquefaction phenomenon (Hungr & *alii*, 2001). Such propagation causes a downward increase of landslides' width and, therefore, accounts for their triangular shape in plan view and, generally, for the mobilization of large volumes of soils.

EXPERIMENTATION OF A SIMPLIFIED VERSION OF THE SL.I.DE. REVISION 2 METHOD

Considering the availability of the digital 1:5.000 cartography, and the effectiveness of the third sliding susceptibility category, a simplified version of the SL.I.DE. method was devised. The difference with respect to the complete method lies in the fact that soil cover absence and discontinuities, including both rock outcrops and roads and tracks, were neither surveyed independently nor verified, but simply extracted from the relative layers of the cartography. In addition, the DTMs were realized with a 10x10 m grid cell, due to the extent of the studied area.

While this approach introduced approximation and GIS implementation problems, it also allowed for a fast, preliminary debris-slide susceptibility evaluation over a 780 km^2 area (cf. 1 in fig. 1), employing limited resources.

The results of this procedure are depicted in figs. 5, 6 and 7. Due to the fact that discontinuities in the soil cover and bedrock outcrops were not actually surveyed or verified, the areas depicted as susceptible to debris slide phenomena are certainly approximate, with a very likely underestimation of actual rock outcrops and slope tracks, as verified in sample slope areas. On the other hand, based on the results obtained by applying the complete SL.I.DE. (revision 2) method at Pizzo d'Alvano, the depicted susceptible areas (in particular, the hollow and sloping areas of the third category) provide a useful indication of the sites which may be most prone to debris slides in case of critical rainfall sequences.

As far as it is very unlikely that a critical, spatially homogeneous rainfall sequence can strike the entire area at the same time, it is equally unlikely that debris slides could be triggered over the whole area at the same time. Nevertheless, the results presented herein could be profitably employed for evaluating the hazard (and then the risk) associated to this type of landslides within limited portions of the studied area (assuming there critical, debris-slide triggering rainfall conditions), by properly combining the described method for assessing the potential source areas with other suitable techniques of run-out prediction. Due to the intense urbanization of the area (at places, also at the foot of steep slopes, covered by volcaniclastic soils, where such landslides already occurred in the past), such combination of methods may suggest to perform cost-benefit analyses of targeted, local soil cover stabilization measures, too, among options for reducing the debris flow-related risk.

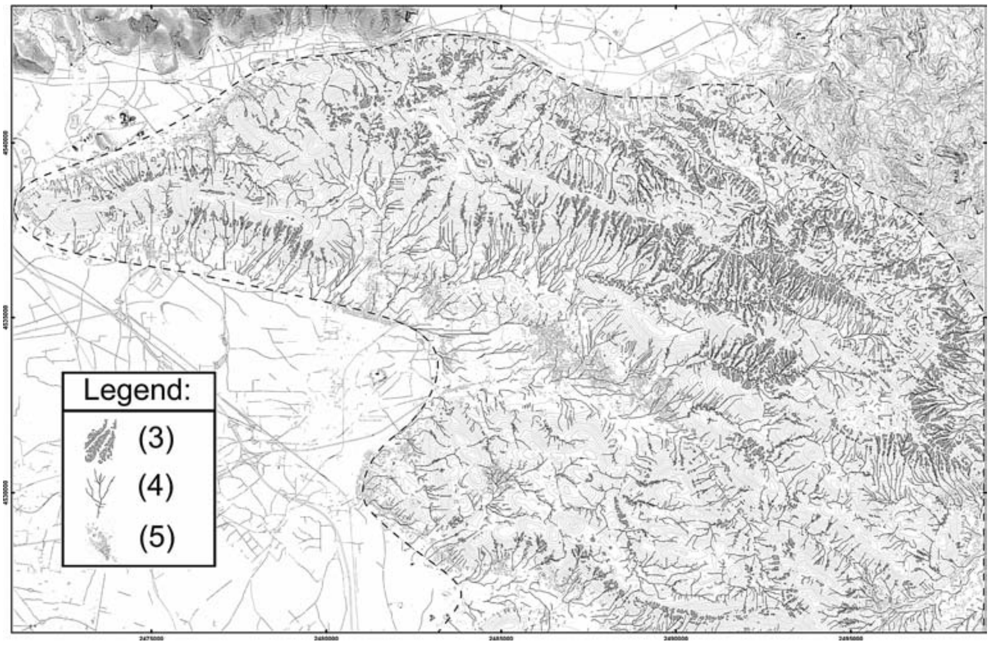


FIG. 5 - Debris-slide susceptibility map (Gauss-Boaga, Rome 1940 datum) of the northern part of the study area (see fig. 1), according to the SL.I.DE. revision 2 simplified method. Key: 3): cf. fig. 4; 4) DTM-derived drainage network; 5) Urbanization. A digital version in color, complete with cat. 1 and 2, is available online at: http://www.progettoslide.unina.it/GeoIt2007/tiff/fig5.zip.

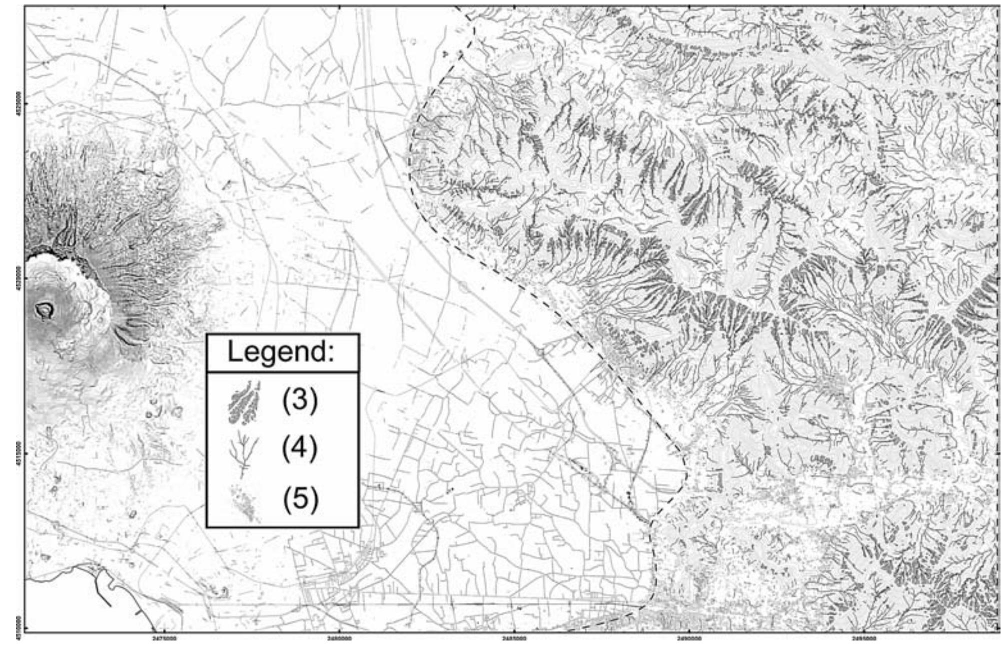


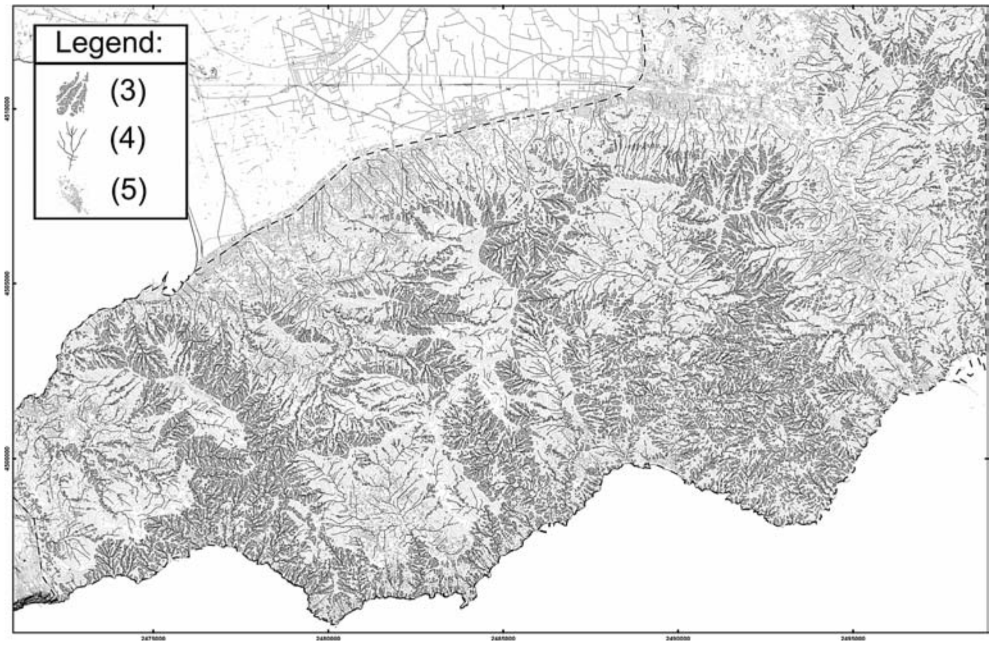
FIG. 6 - Debris-slide susceptibility map (Gauss-Boaga Rome, 1940 datum) of the central part of the study area (see fig. 1), according to the SL.I.DE. revision 2 simplified method. Key: cf. fig. 5. A digital version in color, complete with cat. 1 and 2, is available online at: http://www.progettoslide.unina.it/GeoIt2007/tiff/fig6.zip.

At the time of writing, it was possible to consider only the location of the sources of the main landslides that made victims, from 1986 on (in addition to the May 1998 Pizzo d'Alvano landslides). In fact, the available inventories of debris slide (- debris avalanche) - debris flow phenomena are, in most cases, incomplete and not sufficiently reliable in terms of positioning of the source areas. However, about 80% of the considered recent landslides had their source areas within one or more susceptibility category, as delineated by the SL.I.DE. revision 2 simplified method.

CONCLUSIONS

In this paper, a method for the prediction of the location of the potential source areas of debris slides (that, in most cases, evolve to debris avalanches - debris flows), in case of future critical rainfall sequences, is described, with an example of application to a part of Campania where such phenomena are historically, socially and economically relevant. In its complete form, the method includes the surveying of volcaniclastic soil cover and of its discontinuities, both natural and man-made.

FIG. 7 - Debris-slide susceptibility map (Gauss-Boaga, Rome 1940 datum) of the southern part of the study area (see fig. 1), according to the SL.I.DE. revision 2 simplified method. Key: cf. fig. 5. A digital version in color, complete with cat. 1 and 2, is available online at: http://www.progettoslide.unina.it/GeoIt2007/tiff/fig7.zip.



The method specifically addresses the problem of predicting the source locations of debris slides: for the general public, the complex landslides that often develop from them are mainly considered as «unpredictable», and often remembered confusedly as floods (e.g. in Calcaterra & *alii*, 2003). Instead, the acknowledgement of the fact that debris flows which strike the foothills are commonly generated by debris slides, triggered at distinct locations on mountain slopes, may help in evaluating useful countermeasures.

Several numerical models for simulating the transition of debris slides into debris avalanches and debris flows are nowadays available: they could profitably be applied to potential source areas identified through the method here described, thus allowing to assess the hazardous areas (from the source areas to the deposition zones). Technologies for the stabilization of soil covers on the slopes are also available, and it is possible to perform cost-benefit analyses, that encompass also the feasibility of slope stabilization work, within evaluations of risk-reduction options.

While the SL.I.DE. method was originally developed with regard to the volcaniclastic soil covers of Campania, where the role of discontinuities is generally deemed as particularly relevant to the spatial distribution of source areas of debris slides, it is believed that it could profitably be used (with suitable adaptation and parameters' calibration) for the assessment of the sliding susceptibility also in different, residual and/or colluvial soil, rainfall-triggered shallow landsliding contexts.

Finally, relying on the accuracy and representativeness of DTMs, the SL.I.DE. method may greatly take advantage of high-resolution descriptions of the ground surface, such as those obtainable by means of Lidar ALTM (Light Detection And Ranging Airborne Laser Terrain Mapper) scans of slope areas.

REFERENCES

BAEZA C. & COROMINAS J. (2001) - *Assessment of shallow landslide susceptibility by means of multivariate statistical techniques.* Earth Surface Processes and Landforms, 26, 1251-1263.

BASILE A., MELE G. & TERRIBILE F. (2003) - *Soil hydraulic behaviour of a selected benchmark soil involved in the landslide of Sarno 1998*. Geoderma, 2026, 1-20.

BILOTTA E., CASCINI L., FORESTA V. & SORBINO G. (2005) - *Geotechnical characterisation of pyroclastic soils involved in huge flowslides*. Geotechical & Geology Engineering, 23, 365-402.

CALCATERRA D., PARISE M. & PALMA B. (2003) - *Combining historical and geological data for the assessment of the landslide hazard: a case study from Campania, Italy.* Natural Hazards & Earth System Science, 3, 3-16.

CASAGLI N. (2007) - *Personal communication regarding rainfall over the Ischia island on April 29^{th}-30^{th}, 2006*, resulting from weather radar data belonging to the Italian Dipartimento della Protezione Civile.

CELICO P., GUADAGNO F.M. & VALLARIO A. (1986) - *Proposta di un modello interpretativo per lo studio delle frane nei terreni piroclastici.* Geologia Applicata e Idrogeologia, 22, 73-193.

CHUNG C.F. & FABBRI A.G. (2003) - *Validation of spatial prediction models for landslide hazard mapping*. Natural Hazards, 30, 451-472.

CROSTA G.B. & DAL NEGRO P. (2003) - *Observations and modelling of soil slip-debris flow initiation processes in pyroclastic deposits: the Sarno 1998 event.* Natural Hazards & Earth System Science, 3, 53-69.

CROSTA G.B. & FRATTINI P. (2003) - *Distributed modelling of shallow landslides triggered by intense rainfall.* Natural Hazards & Earth System Science, 3, 81-93.

CRUDEN D.M. & VARNES D.J. (1996) - *Landslide Types and Processes*. In: Turner A.K. & Schuster R.L. (Eds.), «Landslides: Investigation and Mitigation», Transp. Res. Board Spec. Rep. 247, National Research Council, National Academy Press, Washington D.C., USA, p. 36-75.

DAI F.C., LEE C.F. & NGAI Y.Y. (2002) - *Landslide risk assessment and management: an overview.* Engineering Geology, 64, 65-87.

DE VITA P., AGRELLO D. & AMBROSINO F. (2006) - *Landslide susceptibility assessment in ash-fall pyroclastic deposits surrounding Somma-Vesuvio: application of geophysical surveys for soil thickness mapping*. Journal of Applied Geophysics, 59 (2), 126-139.

Di Crescenzo G. & Santo A. (2005) - *Debris slides-rapid earth flows in the carbonate massifs of the Campania region (Southern Italy): morphological and morphometric data for evaluating triggering susceptibility*. Geomorphology, 66, 255-276.

Dietrich W.E. & Sitar N. (1997) - *Geoscience and geotechnical engineering aspects of debris-flow hazard assessment*. In: Chen C. (Ed.), «Proc. 1st Int. Conf. on Debris flow hazard mitigation: mechanics, prediction, and assessment», American Society of Civil Engineers, New York N.Y., USA, p. 656-676.

Ellen D.E. (1988) - *Distribution of debris flows in Marin County.* In: Ellen S.D. & Wieczorek G.F. (Eds.), «Landslides, floods, and marine effects of the storm of January 3-5, 1982, in the San Francisco Bay region, California», U.S. Geological Survey Professional Paper 1434, p. 113-132.

Frattini P., Crosta G.B., Fusi N. & Dal Negro P. (2004) - *Shallow landslides in pyroclastic soils: a distributed modelling approach for hazard assessment*. Engineering Geology, 73, 277-295.

Guadagno F.M. (2000) - *The landslides of 5th May 1998 in Campania, Southern ltaly: natural disaster or also man-induced phenomena?.* Proceedings of International Symposium on Engenering Geology and Hydrology and Natural Disasters, Katmandu (Nepal), 1999, Nepal Geological Society, 22, 463-470.

Guadagno F.M. & Perriello Zampelli S. (2000) - *Triggering Mechanisms of the Landslides that Inundated Sarno, Quindici, Siano and Bracigliano (S. Italy) on May 5-6, 1998*. In: Bromhead E., Dixon N. & Ibsen M.L. (Eds.), «Landslides in Research, Theory and Practice», Proc. 8th Int. Symp. on Landslides, Cardiff (U.K.), 2, Thomas Telford, London, UK, p. 671-676.

Guadagno F.M., Martino S. & Scarascia Mugnozza G. (2003) - *Influence of man-made cuts on the stability of pyroclastic covers (Campania, southern Italy): a numerical modelling approach*. Environmental Geology, 43, 371-384.

Guadagno F.M., Forte R., Revellino P., Fiorillo F. & Focareta M. (2005) - *Some aspects of the initiation of debris avalanches in the Campania Region: the role of morphological slope discontinuities and the development of failure*. Geomorphology, 66, 237-254.

Hungr O., Evans S.G., Bovis M.J. & Hutchinson J.N. (2001) - *A Review of the Classification of Landslides of the Flow Type*. Environmental & Engineering Geoscience, VII (3), 221-238.

Iovine G. (2008) - *Mud-flow and lava-flow susceptibility and hazard mapping through numerical modelling, GIS techniques, historical and geoenvironmental analyses.* In: Sànchez-Marrè M., Béjar J., Comas J., Rizzoli A.E. & Guariso G. (Eds.), «Proc. iEMSs Fourth Biennial Meeting, International Congress on Environmental Modelling and Software» (iEMSs, July 2008). International Environmental Modelling and Software Society, Barcelona, Catalonia, 3, 1447-1460.

Iovino M. & Perriello Zampelli S. (2007) - *The April 30th, 2006, Mt.Vezzi landslides (Ischia Island, Italy) in the context of the sliding susceptibility in Campania*. Italian Journal of Engineering Geology and Environment, 2-2007, 73-91.

Iverson R.M. (2000) - *Landslide triggering by rain infiltration.* Water Resources Research, 36 (7), 1897-1910.

Jakob M. & Hungr O., Eds. (2005) - *Debris-Flow Hazards and Related Phenomena*. Springer-Verlag/Praxis, Berlin, DE.

Mazzarella A. & De Luise E. (2007) - *The meteoric event of 30th April 2006 at Ischia island, Italy*. Italian Journal of Engineering Geology and Environment, 2-2007, 7-14.

Mele G., Basile A., De Mascellis R. & Terribile F. (2007) - *I tagli stradali come fattore d'innesco delle colate rapide di fango in Campania: simulazione 2D del bilancio idrico nel suolo*. In: Versace P. (Ed.), «La mitigazione del rischio da colate di fango a Sarno e negli altri Comuni colpiti dagli eventi del maggio 1998», Commissariato di Governo per la Emergenza Idrogeologica in Campania editore, Napoli, IT, p. 357-372.

Montgomery D.R. & Dietrich W.E. (1994) - *A physically based model for the topographic control on shallow landsliding.* Water Resources Research, 30, 1153-1171.

Montgomery D.R., Dietrich W.E. & Heffner J.T. (2002) - *Piezometric response in shallow bedrock at CB1: Implications for runoff generation and landsliding*. Water Resources Research, 38 (12), 1274-1292.

Moore, I.D., Grayson, R.B., & Landson, A.R. (1991) - *Digital Terrain Modelling: A Review of Hydrological, Geomorphological, and Biological Applications*. Hydrological Processes, 5, 3-30.

Olivares L. & Picarelli L. (2001) - *Susceptivity of Loose Pyroclastic Soils to Static Liquefaction: some preliminary data*. In: Proceedings of International Conference «Landslides: Causes, Impacts and Countermeasures», Davos, Switzerland, 75-86.

Olivares L. & Picarelli L. (2003) - *Shallow flowslides triggered by intense rainfalls on natural slopes covered by loose unsaturated pyroclastic soils*. Géotechnique, 53 (2), 283-287.

Perriello Zampelli S. (2007) - *Sulla possibilità di determinazione della suscettibilità allo scivolamento di suoli piroclastici in Campania.* In: Versace P. (Ed.), «La mitigazione del rischio da colate di fango a Sarno e negli altri Comuni colpiti dagli eventi del maggio 1998», Commissariato di Governo per la Emergenza Idrogeologica in Campania editore, Napoli, IT, p. 373-383.

Revellino P., Hungr O., Guadagno F.M. & Evans S.G. (2004) - *Velocity and runout simulation of destructive debris flows and debris avalanches in pyroclastic deposits, Campania Region, Italy*. Environmental Geology, 45, 295-311.

Revellino P., Guadagno F.M. & Hungr O. (2008) - *Morphological methods and dynamic modelling in landslide hazard assessment of the Campania Apennine carbonate slope*. Landslides, 5, 59-70.

Rolandi G., Petrosino P. & McGeehin J. (1998) - *The interplinian activity at Somma-Vesuvius in the last 3500 years*. Journal of Volcanology and Geothermal Research, 82, 19-52.

Rolandi G., Bartolini F., Cozzolino G., Esposito N. & Sannino D. (2000) - *Sull'origine delle coltri piroclastiche presenti sul versante occidentale del Pizzo d'Alvano.* Quaderni di Geologia Applicata, 7-1, 213-235.

Soeters R. & Van Westen C.J. (1996) - *Slope Instability Recognition, Analysis and Zonation*. In: Turner A.K. & Schuster R.L. (Eds.), «Landslides: Investigation and Mitigation», Transp. Res. Board Spec. Rep. 247, National Research Council, National Academy Press, Washington D.C., USA, 129-176.

Terribile F., Basile A., De Mascellis R., Di Gennaro A., Mele G. & Vingiani S. (2000) - *I suoli delle aree crisi di Quindici e Sarno: proprietà e comportamenti in relazione ai fenomeni franosi del 1998*. Quaderni di Geologia Applicata, 7-1, 59-77.

Torres R., Montgomery D.R., Dietrich W.E., Anderson S.P. & Loague K. (1998) - *Unsaturated zone processes and the hydrologic response of a steep, unchanneled catchment*. Water Resources Research, 34 (8), 1865-1879.

Varnes D.J. (1984) - *Landslide Hazard Zonation: a Review of Principles and Practice*. Unesco Press, Paris, FR.

Zeverbergen L.W. & Thorne C.R. (1987) - *Quantitative Analysis of Land Surface Topography*. Earth Surface Processes and Landforms, 12, 47-56.

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