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Landslide hazard scenarios in Campania

A.M.R.A. S.c.a.r.l.

Prof. Luciano Picarelli
Analisi e Monitoraggio del Rischio Ambientale - AMRA

Centro Euro-Mediterraneo
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Address for correspondence:
Luciano Picarelli, Professor
A.M.R.A. S.c.a.r.l.
Via Nuova Agnano, 11
80125 Napoli
E-mail: luciano.picarelli@amracenter.com

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1. Introduction

Campania is one of the regions in Italy with the highest number of landslides. Leaving aside the very special cases of Vajont (1963) and Val di Stava (1986), in the Alps, a study on the impact of landslides in the last century in Italy (Guzzetti, 2000) shows that the main catastrophes caused by landslides are concentrated in Campania (Fig. 1). Only the landslides occurred in Cetara (1910), Amalfi (1924), Salerno and Vietri sul Mare (1954) and Sarno (1998) caused about 1000 fatalities and missing people. All these events were triggered by precipitations in similar geomophological contexts characterised by relatively steep slopes covered by air-fall pyroclastic soils (notice that the Vajont and Val di Stava were triggered by other causes).
Even though, fortunately, they do not have the same catastrophic consequences in terms of loss of human lives, also landslides in rock and in fine-grained soils are widespread in Campania, causing severe problems, especially for infrastructures and lifelines. This is a good reason to rise the problem, especially when considering that a relevant part of the landslide which involve rock masses and fine grained soils are also caused by precipitations.
This short report has the goal to develop some considerations about the general situation in Campania, with particular reference to the major events caused by precipitations in granular pyroclastic soils for which some lines for future research are proposed.

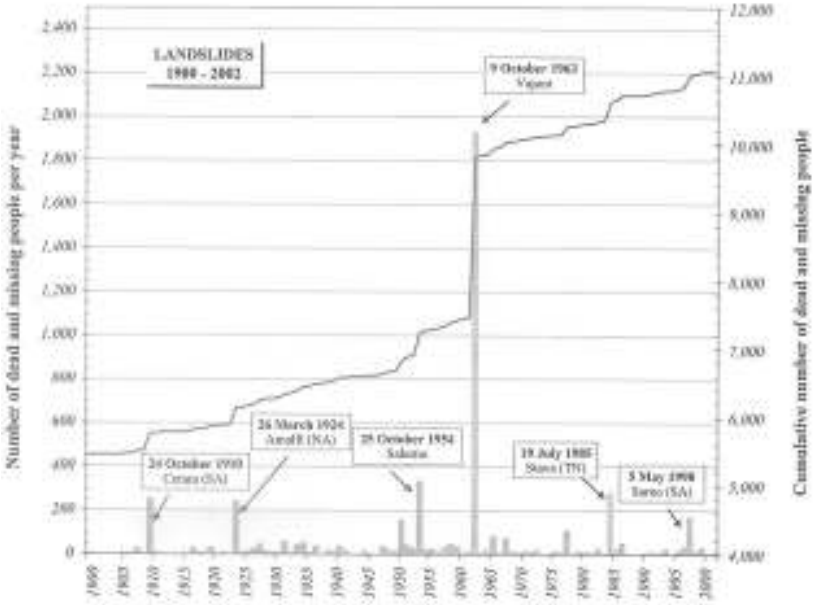

Figure 1. Killer landslides in Italy in the last century (Guzzetti, 2000)

2. Landslides in Campania

Landslides are essentially caused by human activity and by environmental factors, especially rainfalls and earthquakes: rainfalls are the principal cause of slope failure.
Campania is characterised by continuous landslide events spread in the space and in the time. These practically occur in all types of materials, presenting variable features which depend just on the type of material involved, on the morphology of the slope and on the nature of trigger. Figure 2 is a simplified sketch of the main natural deposits outcropping in Campania.

The backbone of the Apennines chain and of the Cilento area are mostly occupied by terrigenous deposits whose principal component consists in highly tectonized argillaceous materials (sheared and highly fissured stiff clays and clay shales). Locally, fractured limestones and cemented conglomerates outcrop. The intermediate zone between the backbone of the Apennines chain and the coast is extensively occupied by pyroclastic soils which cover limestones or terrigenous deposits. The volcanic area around Naples and Procida and Ischia inlands consists of volcanic rocks covered by pyroclastic soils. Finally, Capri inland and Sorrentina Peninsula (Lattary Mts) consist of fractured limestones whose Northern side is covered by pyroclastic soils.

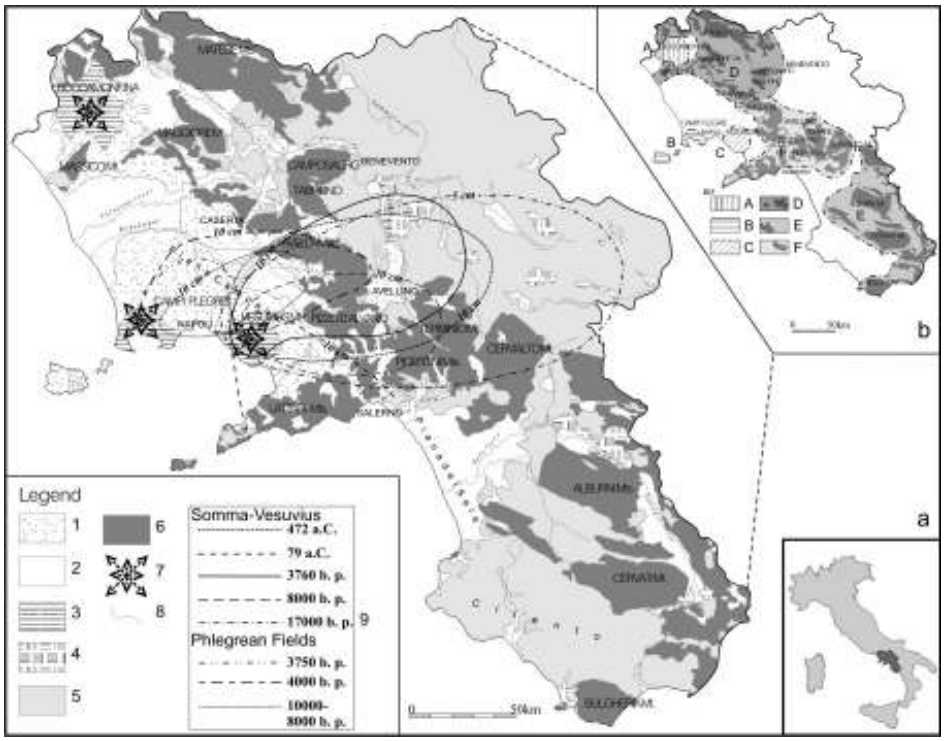

Figure 2. a) Geological map of the Campania Region; b) pyroclastic macro-areas (Picarelli et al., 2008a). 1. Pyroclastic air-fall deposits (Quaternary). 2. Alluvial deposits (Quaternary). 3. Lavas, pyroclastic flows and tuffs (Quaternary). 4. Arenaceous conglomerates (Pliocene). 5. Marly arenaceous terrigenous deposits with clay interbeds (Tertiary). 6. Carbonate rocks (Mesozoic). 7. Volcanic centres. 8. Rivers. 9. Boundaries of the air-fall pyroclastic soils deposited during the eruptions indicated in the same figure

Figure 2b reports a rough macro-zoning of pyroclastic deposits.
In the Roccamonfina volcano area (A) the bedrock is constituted by lava. The pyroclastic products are very old (more than 150 kys) and consist of fine-grained or humified ash; flowslides and liquefied debris flows (Hungr et al., 2001) are not usual.
In the Phlegrean Fields and phlegrean inlands (B), the bedrock consists of tuff covered by pyroclastic soils deposited by flows, surges or fall; the average slope angle is fairly high (about 35°) and tuffaceous cliffs are frequent. There, small to medium-size flowslides can develop.
Coarse pyroclastic materials (pumice and scoria) are spread in the Northern side of the Mt. Somma-Vesuvius system (C) where the slope angles are quite gentle with values higher than 35° only along main drainage channels around the volcano. In such an area only small flowslides can be recognized.
In the macro-area occupied by the Matese, Maggiore, Massico and Tifatini Mts. (D) the calcareous slopes are mantled by air-fall products erupted by Roccamonfina and Phlegrean Fields. On the southern slopes, the largest part of the oldest deposits (about

100 kys) has been almost completely eroded. The northern slopes are covered by weathered ash some tens of centimetres thick; no significant landslides can be recognized.
Because of the large distance from vents, in the macro-area including Marzano Mt., Cilento and Vallo di Diano (E) only very thin deposits of pyroclastic soil (some decimetres) are present; pumices are almost absent, while ash is generally weathered. No significant landslides can be recognized.
The slopes of the macro-area F (Lattari Mts., Sorrentina Peninsula, Picentini Mts., Pizzo d'Alvano Mt., Avella Mts.) have been mantled by the products of several eruptions of the Somma-Vesuvius system in the last 15 ky, the maximum theoretical thickness of primary deposits ranging between 4 and 7 m. In this area steep slopes are repeatedly subjected to flowslides and liquefied debris flows, often resulting in catastrophic events.
The type of landslides in such a complex geomorphological context including so different materials is highly variable; in fact, both slow slope movements and rapid landslides occur.
Fractured limestones and other fractured rocks are essentially subjected to falls, whose occurrence is often unpredictable because they can be triggered by any cause, such as earthquakes and vibrations, rainfalls and freezing, rock deterioration, but also by human activity and by the action of roots. Such landslides are often small in size because of the high degree of rock fracturing and display relatively short travel distances (when compared to the run-out of debris flows in pyroclastic soils).
Tectonized clay shales are subjected to slides, mudslides and lateral spreads. The type of movement depends on the morphology of the slope, but also on the potential of soil deterioration (Picarelli, 2001; Pellegrino et al., 2004; Picarelli and di Maio, 2010): the role of precipitations is prominent in the case of slides and of mudslides. While lateral spreads are always extremely slow being essentially induced by erosion (Picarelli and Urciuoli, 1993) which is naturally slow, mudslides present two different phases: an initial phase, corresponding to triggering or reactivation, which is characterized by a moderate to rapid movement (Cruden and Varnes, 1996), and a long-term phase in which the landslide attains an extremely low rate of movement. Of course, all the intermediate velocity classes may be found between these two extreme conditions. This implies that the landslide may be active for very long times; in fact, chronicles report mudslides which are active since centuries. This has to be related to both the continuous alimentation of the landslide body by debris discharged from the source area and the viscous soil behaviour in the shear zone (Picarelli, 2009).
The main types of landslides in pyroclastic soils are: small falls, debris avalanches (i.e. flow-like movements of dry or wet soil), flowslides (i.e. flow-like movements of liquefied soil), debris flows (i.e. channelled flow-like movements), slides. Generally, they are induced by precipitations. Falls involve high cliffs constituted by slightly lithified soil. Debris avalanches develop along very steep slopes and consist of dry to wet material. Flowslides occur on relatively steep slopes covered by loose soils which can liquefy as a consequence of both saturation due to rainfall and fast deformation: when the mobilised soil mass enters a gully, it turns into a debris flow (Hungr et al., 2001). Slides involve relatively gentle slopes mantled by relatively dense soil.
The most dangerous landslides presenting the largest size and highest velocity, are liquefied debris flows. However, also flowslides and debris avalanches can reach high velocities, even though their travel distance is generally less than that covered by liquefied debris flows.

3. Strategies in landslide risk mitigation

In principle the strategy to adopt for landslide risk mitigation depends on the type, size and velocity of the expected landslide. In some way, nature of soil, type of landslide and velocity are interrelated. Summing up previous considerations, and essentially looking to the soils widespread in Campania (Fig. 2):

- fractured rocks, tuff and slightly cemented pyroclastic soils are mainly subjected to falls, but also to topples and slides, all being quite rapid;
- stiff highly fissured clays and clay shales are subjected to slides and mudslides which are moderate to rapid, or to active or reactivated slides which are generally slow to extremely slow;
- pyroclastic soils are mainly subjected to debris avalanches, debris flows, flowslides, which range from rapid to extremely rapid; in these deposits moderate slides may also occur.

In each class of movement minor differences can be found, depending on both geomophological and geotechnical details. This is a prominent point for the case of pyroclastic soils whose post-failure behaviour can be highly variable. This point will be resumed below.
The selection of the best approach for risk mitigation is a crucial choice which must be undertaken by expert people. In any case, some simple guidelines based on the type of expected landslide, would very useful.
Just as an example, in the case of rapid to extremely rapid landslides, the following strategies can be adopted:

a) slope stabilization by active works, which allows to influence the hazard by increasing the safety factor: metallic or plastic fences, retaining works, nailing, drainage and reprofiling are the most adopted stabilization criteria;
b) protection of the exposed goods by passive works, which allows to reduce the exposition or the vulnerability: barriers, check dams and large sedimentation reservoirs located at the foot of tracks are often built;
c) evacuation of areas at risk which allows to reduce exposition;
d) early warning systems based on timely landslide prediction, alerting and adoption of protection measures, which allows to temporarily reduce the exposition and the risk.

Such strategies, in principle, may be adopted in the case of moderate to slow landslides, but the measure which is by far the most usually used is slope stabilization by active works.
In the case of very slow and extremely slow landslides, besides slope stabilization, living with landslides is sometimes accepted, especially if measures of reinforcement of the structures which are threatened by slope movements are adopted.
Therefore, an appropriate zoning of the territory can help for a preliminary evaluation of the class of problems which can be encountered in land protection. Some considerations will be presented in the following with reference to the case of pyroclastic soils looking to further researches on this topic.

4. Factors affecting landslide prediction and zoning in pyroclastic soils

The analysis of the hydrological response of sloping unsaturated soils shows the complex role played by a number of geometrical and geotechnical factors, such as the slope angle, the thickness and stratigraphy of the cover, the permeability of the bedrock and the

hydraulic and mechanical properties of the soil. A fundamental role is also played by the features of the precipitation regime: in fact, the rainfall intensity, duration and distribution regulate the quantity and depth of infiltration. Therefore, the prediction of the onset of slope failure is a very difficult exercise, which is nevertheless crucial in order to set up effective procedures for the protection of lives and for the integrity of structures and infrastructures.

The case of the infinite slope is very useful to clarify some aspects of the problem. For a given cohesionless saturated soil and for established seepage conditions (for instance 1D seepage parallel to the ground surface with constant depth of the groundwater table), the safety conditions depend on the ratio between the friction angle of soil, φ', and the slope angle, α: in fact, the safety factor decreases linearly as the slope angle increases. However, for unsaturated slope subject to rainfall, such a relationship does not hold since the soil strength is not constant, depending on the degree of saturation which affects the apparent cohesion and varies with time as a function of the rainfall history and features, of the stratigraphy and thickness of the cover, of the hydraulic properties of soil and of the permeability of the bedrock.

Figure 3, which is based on field data, highlights the role of the bedrock. It reports the angle of a number of slopes in unsaturated volcanic which experienced rainfall-induced landslides, as a function of the nature of the bedrock. It shows that the critical slope angle, α_{crit}, for which a landslide occurs is relatively high where the bedrock consists of fractured limestone (which is relatively pervious), and is much gentler where the bedrock is argillaceous flysch (which is relatively impervious). This calls for the characteristics of the seepage process induced by infiltration.

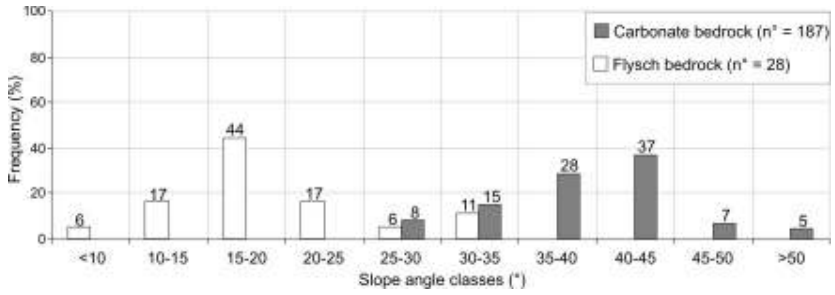

Figure 3. Distribution of the slope angle of flowslides occurred over a carbonatic or a flysch bedrock (Picarelli et al., 2008a)

It is well known that in the case of vertical flow in cohesionless saturated soil, the critical slope angle is equal to the friction angle of soil, i.e. something less than 40° in the case of pyroclastic soils (35°-39°); in contrast, for groundwater table at the ground surface and flow parallel to it, $\alpha_{crit}=\arctan((\gamma' \tan\varphi')/\gamma_{sat}) \approx \arctan(0.4\tan\varphi') \approx 15°\text{-}16°$. An intermediate value between 15°-16° and 35°-39° can be calculated for depths of the groundwater table intermediate between zero and the depth of the bedrock.

Based on such considerations, the figure suggests that in the highest number of cases for which the pyroclastic cover overlies a fractured carbonate bedrock, the slope failed after saturation caused by vertical flow: this can be justified only by the presence of a pervious lowermost boundary. For a slope angle higher than 40°, failure probably occurred prior to complete saturation; for α much less than 40° (more or less 20% of the considered cases), rupture occurred for a water flow parallel to the ground surface and intermediate depth of the groundwater table. The first case (α>40°) may correspond to two different conditions: i) rupture during the infiltration process before the humid front reaches the bedrock; ii) rupture within a relatively pervious pyroclastic cover, i.e. for a degree of saturation less than 100%, even after the humid front reached the bedrock. The failures occurred for

α_{crit}<<40° suggest that a less pervious layer (for instance, a weathered ash horizon) was probably located at the interface with the bedrock or at an intermediate depth, creating the conditions for flow parallel to the bedrock.
In the case of pyroclastic cover resting on a relatively impervious bedrock (flysch), it appears clear that the failure occurred for flow parallel to the bedrock, i.e. after the humid front reached the bedrock. The figure suggests also that the highest number of landslides corresponds to groundwater table at the ground surface (α=15°-20°), but that a number of them (more than 30% of the considered cases) occurred for groundwater table at an intermediate depth between the ground surface and the bedrock. Finally, some landslides (around 20%) occurred for α<15°, which can be explained only assuming that they were triggered by an impact or by progressive failure.
These considerations confirm the complexity of the problem to recognize the slopes which are susceptible to landslide, and clarifies why in areas occupied by pyroclastic soils covering fractured limestones landslides involve steep slopes, while in areas occupied by flysch they can involve gentle slopes. However, since at the beginning of the process the seepage is essentially vertical whatever is the lowermost boundary conditions, the establishment of a 2D condition requires a relatively thin and pervious soil cover or an intermediate less pervious layer and/or relatively continuous and long-lasting precipitations allowing water to reach the bedrock.
This is hence a factor which involves the probability of failure (i.e. the hazard) which decreases for short rainfall, deep uniform cover and relatively gentle slope. Numerical analyses (AMRA, 2009) fully confirm the role of the nature of soil on the probability of failure. In fact, the hydraulic conductivity, which in unsaturated soils is a function of the water content, governs the rate of infiltration and the time for reaching the base of the bedrock: therefore, the coupling of the permeability function and of the intensity and duration of precipitations has a fundamental role on the time to failure.
The nature of soil has also a prominent influence on the velocity of the movements (i.e. on the risk) which is naturally higher in the case of brittle soils and steep slopes. In fact, laboratory experiments (Eckersley, 1990; Wang and Sassa, 2001; Picarelli et al., 2008b) show that some of the factors listed above affect also the intensity of the landslide (velocity) thus the risk. As a matter of fact, literature demonstrates that the triggering of flowslides and liquefied debris flows, the fastest and most dangerous landslides, depends on the building up of positive excess pore pressures (static liquefaction) which determines a drop of the shear strength and a strong acceleration which in turn may cause soil fluidization (Iverson, 1997; Musso and Olivares, 2004). The consequence of this is the attaining of a high velocity even over short distances, and the propagation downhill of the liquefaction process (and the involvement of large soil masses, i.e. the landslide size) through downslope load transfer.
The occurrence of liquefaction is likely in very loose granular and non plastic soils (Poulos, 1981; Sladen et al., 1985; Yamamuro and Lade, 1997). This implies that the pyroclastic soils which are prone to liquefaction are non weathered air-fall volcanic ashes (Olivares and Picarelli, 2001; Picarelli et al., 2008a). Based on laboratory tests, Picarelli et al. (2008c) show that for thickness up to 2-3 m, a void ratio higher than 1.8 should be high enough to cause liquefaction. A last important aspect is that liquefaction occurs only in saturated or quasi-saturated soils. This implies that in the case of very steep slopes, for which failure occurs before saturation, liquefaction cannot take place (Olivares et al., 2002). Based on typical characteristic curves and friction angles, Picarelli et al. (2008c) show that in the case of infinite slopes up to 45° and less than 2 m thick, the degree of saturation at failure should be large enough to favour liquefaction.

Finally, as anticipated, the rainfall intensity is another important aspect which governs the problem; in fact for very high rainfall intensity, infiltration causes saturation and failure of the shallowest layers giving rise only to small landslides (Sharma and Nagakawa, 2010).
In conclusion, the susceptibility, hazard and risk of rainfall-triggered landslides in pyroclastic covers are a complex function of a number of factors concerning the morphological features of the area (the slope angle in the case of infinite slopes), the stratigraphy, the hydraulic and mechanical properties of soil and the features of the rainfall (recent rainfall history, intensity and duration of present precipitations).

5. Some good reasons for future research

All these considerations show the complexity of the problem of zoning and predicting of rainfall-induced landsides. At the same time, they make clear the fact that a good regional zoning accounting for all these aspects can and must be carried out, being highly beneficial to individuate the critical zones (susceptible zones) and the probability of failure (hazard) inside.
Zoning of rainfall-induced landslide susceptible slopes should account for the following aspects:

- the morphological features of the territory, i.e. the steepness of the slopes and the thickness of the covers;
- the nature of the pyroclastic covers, looking at the stratigraphy, the hydraulic conductivity, the density and shear strength of soils;
- the nature of the bedrock, i.e. its hydraulic conductivity.

Susceptible slopes are all those areas where a landslide can occur in the worst meteorological conditions. For instance, for impervious bedrock and infinite slope in cohesionless soils, this could occur for slope angles higher than the friction angle of soil: as discussed above, for γ_{sat}=16 kN/m^3 and φ'=38°, susceptible slopes have an angle higher than 16°. Since, as shown, liquefaction occurrence depends on soil features, mainly grain size, plasticity and void ratio of soil an on the state of stress, thus on the thickness of the cover, the susceptibility to landslide does not coincide with the susceptibility to liquefaction, i.e. to flow-like landslide (flowslides and liquefied debris flows), which can occur only within a part of landslide susceptible zones (Picarelli et al., 2008c). As shown, this can be obtained bearing on good data about morphological features of slopes (which can be easily obtained), thickness, stratigraphy and soil features. General geological data are already available (Picarelli et al., 2008a); further data can be collected.
Hazard mapping is different since this depends on the probability of landslide occurrence. In fact, the hazard could be based on the probability that a rainfall can lead to failure a landslide susceptible slope. Besides previous factors, this depends also on the permeability function of soils, on initial conditions (suction and/or water content) and intensity and duration of incoming rainfall. The initial conditions in a given zone can be measured through networks of tensiometers or can be obtained through analysis of infiltration based on the recent rainfall history (Pagano et al., 2010). Finally, the hazard should be strictly related to the probability that the critical precipitation (duration and intensity) obtained through an analysis starting from present initial conditions will occur. Therefore the hazard could be obtained in real time based on short-term weather forecasting.
The risk depends on propagation, landslide size, exposure and vulnerability. Therefore, the risk too can be obtained through real-time analysis of propagation and impact of the recognized potential landslide.

These important elements can be obtained only after accurate geomorphological and geotechnical investigations within the landslide susceptible zones.
Based on such considerations, advanced studies should be launched, addressed to a regional characterization of covers and bedrock and further development of criteria for short-term precipitation forecasting and hazard mapping.

6. Conclusive remarks

Rainfall-induced landslides are very usual in Campania in different types of deposits either in soils either in rock masses, with particular reference to pyroclastic deposits, highly OC clays and fractures limestones. However, the risk is much higher in the case of pyroclastic soils. This requires advanced zoning of landslide hazard areas and the setting up of procedures for prediction of landslide triggering. Based on the results of a three years research, some criteria for mapping of hazard areas have been discussed. They require a good knowledge of the morphological and geotecnical features of the territory and on further development of criteria for short-term precipitation forecasting and hazard mapping.

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