

Debris flows and debris avalanches initiation and runout susceptibility assessment in Campania region (Italy)

Rita Tufano¹, Davide Mazza¹, Francesco Maria Guadagno¹, Pantaleone De Vita², Giacomo Russo² and Paola Revellino^{1*}

¹Department of Sciences and Technologies, University of Sannio, Benevento, Italy

²Department of Earth, Environmental and Resource Sciences, Federico II University of Naples, Naples, Italy

Abstract. Sectors of the Campania region (southern Italy), where pyroclastic airfall deposits cover carbonate slopes, have frequently experienced debris avalanches and debris flows. These landslides are triggered by heavy rainfall and in the last century caused severe destruction and hundreds of deaths. Their occurrence is controlled by the interaction of several factors, both natural and human induced. The initial failure is linked with the presence of morphological discontinuities such as rocky scarps and road cuts, which interrupt the stratigraphical continuity of an “infinite slope”. Here the main criteria for susceptibility analysis are defined trying to develop a procedure for identify highly-susceptible sources, runout and invasion areas.

1 Introduction

Landslide hazard of the Campania carbonate slopes (southern Italy) covered by pyroclastic deposits is mainly related to the occurrence of high-velocity debris avalanches and debris flows. Historical analyses have shown that landslides are spatially and temporally very common and remarkably similar to each other in terms of style, morphology, and materials involved. The initial landsliding process is controlled by the interaction of numerous factors, both natural and human induced.

Geomorphological settings play a decisive role in locating the source failures of landslides. On this basis, landslide hazard can be assessed by the following crucial approaches: a) recognition of the geomorphological controlling factors in terms of source areas and flows paths; b) definition of landslide intensity parameters in terms of velocities, volumes and runout distance. An approach combining geomorphology, slope stability analysis and numerical runout modelling is here adopted with the aims to identify possible landslide source areas and simulate landslide intensity scenarios. Moreover, to predict the runout behaviour of potential debris avalanches-debris flows by using a dynamic model previously calibrated on observed events.

2 Landslide features

2.1 Geological predisposing factors

The Campania Apennines are characterised by calcareous-dolomitic mountains formed by monoclinical series which are mantled by a thin veneer of air-fall

material, such as ash, lapilli and pumice, and ignimbrite-type flows, principally linked to cyclic explosive volcanic activity of the Phlegrean Fields and Somma-Vesuvius Volcanoes. This results in a typical geomorphological setting where the pyroclastic soils overlay on the bedrock at angles close to the frictional angle of the material. Even though the pyroclastic materials strongly smooth slope irregularities, the morphology of the calcareous bedrock is manifest by scarps and deep gullies.

The fertility of the pyroclastic mantle has constantly encouraged the use of slopes for agricultural and forestry purposes, so that mechanised forest management practices have favoured the growth of a dense track network, significantly unsettling the delicate equilibrium of slopes.

Detailed surveys carried out demonstrate the role of these morphological discontinuities both on water circulation and on the stability of masses [1].

2.2 Landslide mechanisms

The failure phenomena occurring in the pyroclastic soil exhibits a distinctive general behaviour. Analogies concern landslide type (initial translational slides evolving into viscous, fluid flows), material involved, confinement in gullies or steep stream channels if present, high velocity and high erosive capacity. Moreover, they are generally triggered by heavy and prolonged rainfalls whose effects on slope stability are controlled by antecedent soil hydrological conditions [2]. The initial movement consists of a translational slide of thin but relatively wide segments of the pyroclastic cover (thickness from some decimetres up to 2 m). The initial mass is able to destabilize the

* Corresponding author: paola.revellino@unisannio.it

pyroclastic cover downslope. As a result, initial slides soon transform into extremely rapid, fluid debris avalanches [3], increasing in volume by eroding the slope soil cover. The landslide material can flow along the open slopes or become channelled into gullies where, if incorporating water, can transform in debris flows and hyperconcentrated flows.

In most landslide cases, initial translational slides were triggered at the edges of morphological discontinuities (natural scarps or road cuts) (e.g. [4]) and they were linked to kinematic freedom conditions of the pyroclastic masses in such morphological contexts (Fig. 1). A less-frequent scenario in the region consists of instabilities occurring immediately downslope of cuts for tracks and involving road-fill materials. Typical morphological settings recognised in landslide source areas are shown in Fig.1.

Both surficial and groundwater circulation play a fundamental role in triggering the phenomena. Field observations show that along the slopes water can concentrate and infiltrate, inducing the development of pore pressure for the initial instabilities and supplying water for fluidification of masses.

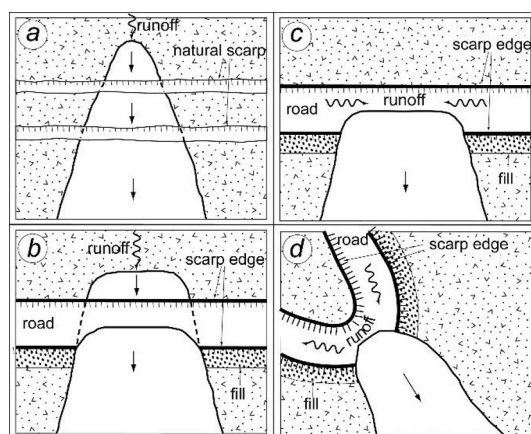


Fig. 1. The morphological setting of the main source area types for the Campania landslides: (a) above natural scarp; (b) above man-made cut; (c) involving fills, in correspondence of "sagging rope" segment of pathways; and (d) involving fills in the road bends.

3 Criteria in susceptibility maps

Analyses carried out on historical and recent debris avalanches/flows in Campania region permit to select some criteria in locating the source areas of potential future occurrences. It is also true that a single triggering model is not enough to explain the initial landslide mechanism. A complex variety of models should rather be needed, making susceptibility mapping quite difficult and uncertain.

Generally speaking, prediction of the starting points of potential landslides should be made through field observations, by identifying critical locations within the typical morphological settings recognised in the failure areas. Often, such critical locations can be recognized by open cracks, points of preferential water run-off or seepage, soil masses displaced forward and overhanging at the scarp edges. In particular, the criteria should be referred to: i) slope angles; ii)

geomorphological origin of the slope (for examples fault or dip slopes, open slopes, etc.); iii) occurrence of pyroclastic deposits and their lithological and geometrical characteristics; iv) occurrence and geometrical characteristic of morphological discontinuities of the bedrock (e.g. natural scarps); v) occurrence and characteristic of human-induced morphologies; vi) possibility and/or evidence of concentrated, superficial water flows.

4 Study area

The selected test area is located in the southern sector of Mt. Sole close to Salerno town, where geomorphological factors controlling landslide susceptibility were identified. The test area comprises the Olivieri Valley incised by deep gullies that flow into the main N-S direction valley floor at about 200 m a.s.l.. Quaternary and Holocene deposits consisting mainly of in-situ and reworked pyroclastic soils and colluvium, discontinuously cover the carbonate bedrock. Their thickness quite varies depending on the slope angle and the morphological setting of the bedrock (Fig. 2), according to [5,6]. In particular, the greatest thickness (>2 m) is found in the lower part of the slope where the slope angle ranges from 0° to 20°, while thickness between 0.5 and 2 m characterizes the intermediate sector of the slope, not interested by gullies, for which the slope angle ranges from 20° to 35°. Conversely, the outcrop of the bedrock and gullies are characterized by a slope angle greater than 45° and the absence of cover. Similar conditions are also recognized at the base of the slope where man-made cuts occur. Finally, trackways (i.e. man-made road cuts) in both the upper and middle sectors of the test area further entail discontinuity in the cover.

4.1 Micro-morphological factors map

Based on the procedure calibrated by [7] on areas involved by landslides in a similar geo-morphological context (i.e. Avella Mt.s), micro-morphological factors, intended as local morphological discontinuities collected through a detailed field survey, were recognized because identified as controlling landslide susceptibility at the source areas (Fig. 2). Such procedure was selected because of the topographic, geometric, morphological and lithological data available for the sector of slope potentially susceptible of landslide triggering. At this aim, identified morphological discontinuities (scarps) of the carbonate bedrock were grouped into two classes on the basis of their height: a) $H > 5$ m; and b) $H < 5$ m. Scarp height is a morphological criterion because controlling the impact energy of masses. It should be noted that along scarps rock falls may also occur, which can have similar destabilizing effects. Artificial cuts were carefully identified and mapped, since they represent one of the most important details influencing landslide occurrence in the pyroclastic soils of the Campania region [1]. Since they act as preferential lines of water infiltration into the more permeable pyroclastic layers, the most critical

locations were identified at bends and along "sagging rope" segments of the zigzag pathways. Finally, by means of field inspections, gully segments were distinguished based on the presence or absence of debris material deposited on the gully floors. The existence of debris filling the gullies leads to more hazardous situations, since they can increase the magnitude of a potential landslide event by entrainment during motion.

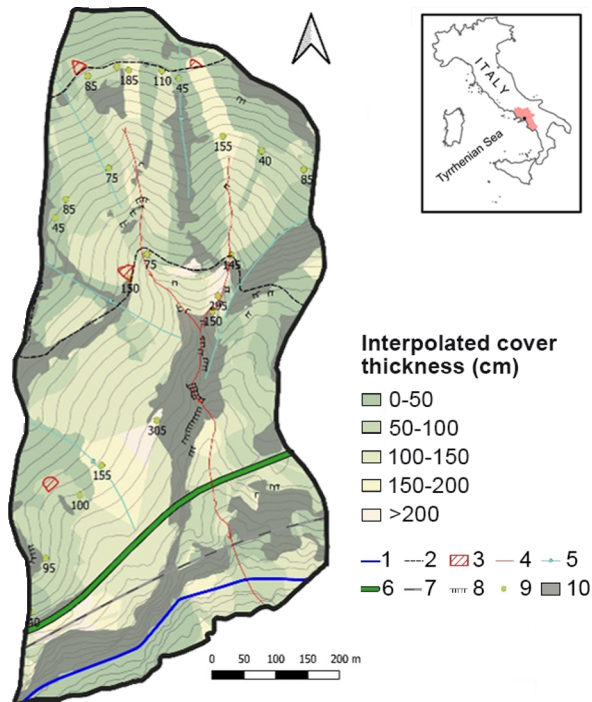


Fig. 2. Map of micro-morphological factors controlling landslide susceptibility in the test area of the Oliviero Valley: (1) road; (2) trackway; (3) landslide source area; (4) gully; (5) watershed; (6) railroad; (7) highway; (8) natural scarp; (9) measured cover thickness; (10) bedrock outcrop/cemented cover area.

4.2 Initiation susceptibility

Stability analysis of pyroclastic cover was conducted based on the spatial distribution of micro-morphological factors most critical for landslide triggering. Due to the stratigraphic setting of the pyroclastic cover, stability analysis was carried out by infinite slope approach (e.g. [8,9]). In particular, the factor of safety (FoS) was estimated considering the unified effective stress criterion incorporating the effect of partially saturated soil conditions (e.g. [10]) for which shear strength is a function of both normal stress and suction contribution [11]. Accordingly, the failure criterion can be written as:

$$\tau = c' + [(\sigma - u_a) - \sigma_s] \tan \phi' \quad (1)$$

where τ is the shear strength, c' is the effective cohesion, σ is the total stress, ϕ' is the friction angle and σ_s is the suction stress, equivalent to pore-water pressure, u_w , for saturated conditions:

$$\sigma_s = -(u_a - u_w) \quad \text{for } u_a - u_w \leq 0 \quad (2)$$

while it corresponds to the product of effective saturation degree (θ_e) and the matric suction ($u_a - u_w$) for partially saturated conditions:

$$\sigma_s = -\theta_e (u_a - u_w) \quad \text{for } u_a - u_w > 0 \quad (3)$$

The main physical properties (porosity $n = 53\%$, natural unit weight $\gamma = 15 \text{ kN/m}^3$, natural water content $w = 13\%$) of the pyroclastic layer were determined in laboratory on representative samples. The assumed shear strength parameters, determined by means of direct shear tests on saturated undisturbed samples, were $\phi' = 37^\circ$ for friction angle and $c' = 2,4 \text{ kPa}$ for cohesion, are in good agreement with parameters reported by [12,13] for similar pyroclastic formations. The water retention curve implemented in the numerical code was related to the grain size distribution of the pyroclastic layer. Suction was assumed constant with depth and equal to 36 kPa , corresponding to an effective degree of saturation $S_r = 0.7$ on the water retention curve, corresponding to the representative value of the pyroclastic soils in the area. Calculated FoS, also depending on slope angle and cover thickness of the possible sources area, was reclassified to define different susceptibility classes. In particular, four susceptibility classes from the higher to the lower FoS values are marked for the Oliviero Valley test area (Fig. 3). Results identify highly-susceptible source areas as mostly localized above and long trackways, in the middle and upper part of the slope above natural scarps and in the eastern middle and upper part of the slope, probably linked to the possible superficial water flow.

Susceptible areas to initial landsliding are considered sources of potential initial debris slides which trigger the following avalanches-debris flow stages. The runout susceptibility of the latter is further estimated.

4.3 Runout susceptibility

In order to define the most susceptible to runout areas, the geometry of the potential source areas was defined based on the minimum and maximum values of apex angle as estimated by [1] for each typical micro-morphological factor (i.e. natural scarps, man-made road cut, and material filling). Subsequently, propagation modeling was completed using DAN-3D software [14] following the procedure described in [15]. DAN-3D is based on a continuum numerical solution of the depth-averaged Lagrangian equations of motion, which allows the propagating landslide mass to be simulated as a hypothetical material governed by a simple rheological relationship. In this case, the rheological model selected is the Voellmy model. Such model considers the resisting stress at the base of the propagating flow as:

$$\tau = \gamma H \left(\cos \alpha + \frac{\alpha_c}{g} \right) \mu + \gamma \frac{v^2}{\xi} \quad (4)$$

where τ is the resisting stress at the base of the flow, γ is the unit weight of the flowing material, H is the flow depth, α is the slope angle, μ the dynamic friction coefficient related to the total normal stress at the base of the flow, α_c is the centrifugal acceleration resulting from the vertical curvature of the flow path, and ξ is a turbulence coefficient. The dynamic friction coefficient and turbulence coefficient were set according to those determined by [13] ($\mu=0.07$; $\xi=200 \text{ m/s}^2$) in

geomorphologically similar areas (i.e. Sarno-Quindici and Cervinara Mt.s), estimated through back-analysis of past events using a trial-and-error procedure.

The thickness of the initiating debris slides and erosion depth downslope from the source area was set according to pyroclastic cover thickness measured during field surveys. Moreover, two different scenarios were considered for each source area: 1) maximum intensity scenario, for which source area was defined by the maximum values of apex angle and by the total entrainment of the slope and gully material along the landslide path considering a maximum soil thickness; 2) medium intensity scenario, for which source area was defined by the minimum values of apex angle and by the total entrainment of the slope and gully material along the landslide path considering a medium soil thickness.

The outcomes of the dynamic analysis in terms of runout distance, maximum landslide velocity, and deposit thickness for each modeled event in the selected test area, allow the zonation of runout susceptible areas. To this aim, four susceptibility classes were defined for which the maximum intensity scenario was associated with high susceptibility, while the medium intensity scenario to the very high susceptibility class (Fig. 3).

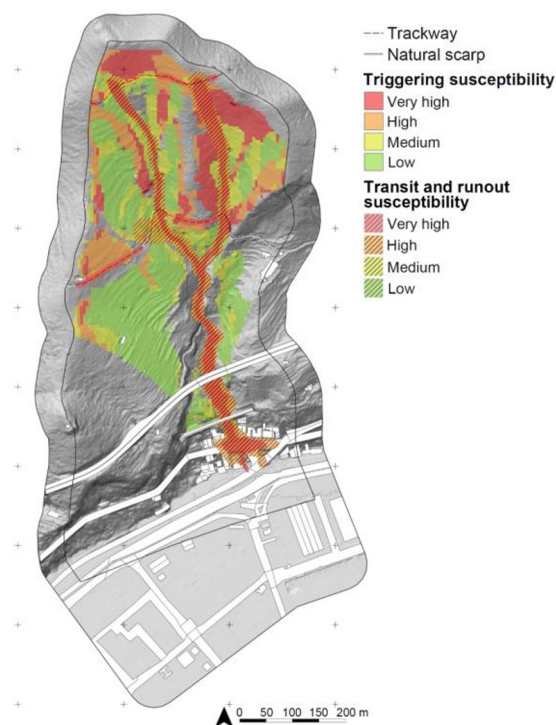


Fig. 3. Initiation and runout susceptibility map of debris avalanches and debris flows in the Oliviero Valley test area.

5 Conclusions

This paper presents a hybrid procedure for initiation and runout susceptibility to debris avalanche-debris flow assessment based on geomorphological and slope stability analysis with the aim to identify possible landslide source areas, and numerical modeling for predicting the runout behavior of potential instability.

Especially, dynamic modeling conducted with DAN-3D software using Voellmy rheological model enables the evaluation of runout distance, maximum landslide velocity, and deposit thickness that allow

defining different intensity scenarios of events useful in the evaluation of possible impacts to structure and infrastructure. It is important to note that the dynamic model applies only to the specific conditions of the Campania debris flows and debris avalanches due to the peculiar characteristics of pyroclastic deposits and their geomorphological setting. The described procedure is reproducible in similar geomorphological frameworks for which data about geological, geomorphological, and geotechnical features are available.

Finally, if initiation susceptibility mapping appears to be fundamental in the land-use planning context, the definition of kinematic and dynamic characters of events also appears as a priority for the safeguard of structures and infrastructures potentially involved in landslide phenomena.

References

1. F.M. Guadagno, R. Forte, P. Revellino, F. Fiorillo, M. Focareta. *Geomorph.* **66**, 237–254 (2005).
2. P. De Vita, F. Fusco, R. Tufano, D. Cusano. *Water*, **10**, 1140 (2018).
3. O. Hungr, S.G. Evans, M. Bovis, J.N. Hutchinson. *Environ Eng Geosci* **7** (3):1–18 (2001).
4. F. Fiorillo, L. Guerriero, L. Capobianco, M. Pagnozzi, P. Revellino, F. Russo, F. M. Guadagno. *J. of Maps* **15**(2), 530-537 (2019).
5. P. De Vita, D. Agrello, F. Ambrosino. *J. Appl. Geophys.* **59**:126–139 (2006).
6. P. De Vita, M Nappi. *Regional distribution of ash-fall pyroclastic deposits in Campania (southern Italy) for landslide susceptibility assessment*. In: Margottini C, Canuti P, Sassa K (eds) *Landslide science and practice. Spatial analysis and modelling*. Springer, Berlin, **3**:103–110 (2013).
7. P. Revellino, F.M. Guadagno, O. Hungr. *Landsl.* **5**:59-70 (2008).
8. R. Tufano, F. Fusco, P. De Vita. *Rend. Onl. Soc. Geol. It.* **41**:210–213 (2016).
9. R. Tufano, G. Formetta, D. Calcaterra, P. De Vita. *Landsl.* **18**:3367–3380 (2021).
10. S.K. Vanapalli, D.G. Fredlund, D.E. Pufahl, A.W. Clifton. *Can. Geotech. J.* **33**(3):379–392 (1996).
11. N. Lu, J.W. Godt, D.T. Wu. *Water Resour. Res.* **46** (5), (2010).
12. S. Ferlisi, G. De Chiara. *Risk analysis for rainfall-induced slope instabilities in coarse-grained soils: Practice and perspectives in Italy*. In *Landslides and Engineered Slopes. Experience, Theory and Practice – Aversa et al. (Eds) Ass. Geot. It., Rome, Italy* (2016).
13. P. Revellino, O. Hungr, F.M. Guadagno, S.G. Evans. *Envir. Geol.* **45**(3), 295-311 (2004).
14. S. McDougall, O. Hungr. *Can. Geotech. J.* **41**(6), 1084-1097 (2004).
15. P. Revellino, L. Guerriero, G. Grelle, O. Hungr, F. Fiorillo, L. Esposito, F.M. Guadagno. *Ital. J. Geosci. (Boll. Soc. Geol. It.)*, **132**, 336-379 (2013).