

Landslide susceptibility assessment in ash-fall pyroclastic deposits surrounding Mount Somma-Vesuvius: Application of geophysical surveys for soil thickness mapping

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Abstract

Along the steep slopes of the carbonate mountains that surround the Campanian Plain and Mount Somma-Vesuvius, rainfall-triggered debris slides occur in unconsolidated ash-fall pyroclastic deposits. The initial debris slides evolve into debris flows that often cause significant property damage and loss of human life in the towns located at the foot of the slopes. In this particular geological situation, the pyroclastic soil thickness, the slope angle, and the morphological variations of the slope profile are the most important factors that contribute to landslide susceptibility.

In this paper, the results of an experimental application of shallow resistivity and refraction seismic soundings in mapping the thickness of pyroclastic soils are presented. These geophysical methods are proposed as low-cost and versatile methods to be used in the difficult morphological conditions of the steep slopes in which debris-slides initiate.

The methods have been used experimentally in a sample area located on the upper slope of Mount Pizzo d'Alvano, from which debris flows initiated that dramatically hit the town of Sarno on 5–6 May 1998.

The inversion of geoelectrical soundings has been calibrated with resistivity values measured directly on pyroclastic outcrops and with soil thickness estimations derived from refraction seismic soundings and from the application of a mobile dynamic penetrometer.

The results of the field experimentation can be summarised as follows: (i) unconsolidated ash-fall pyroclastic deposits, ranging in particle size from fine ash to lapilli, can be differentiated from fractured carbonate bedrock by means of electrical resistivity and velocity values of longitudinal seismic waves; (ii) thickness of ash-fall pyroclastic soils can be empirically related to the slope angle using an inverse relationship; and (iii) the empirical model has been applied to Digital Elevation Model data, allowing pyroclastic soil thickness mapping in the sample area.

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1. Introduction

The mountains that surround the Campanian Plain of Southern Italy, a large flat area rounding Mount

Somma-Vesuvius, are characterised by a particular geological condition consisting of unconsolidated ash-fall pyroclastic overburdens derived from the Somma-Vesuvius eruptions, especially in the southern and eastern sectors of the Plain. These mountains, belonging to the Lattari, Sarno, and the Salerno Mountain range, geologically comprise a Mesozoic carbonate sedimentary

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series and have a variegated morphology with very steep slopes, deriving from erosional evolution of the original fault-line scarps, which caused bedrock subsidence toward the centre of the Plain. Along these slopes, the ash-fall pyroclastic soils are generally unstable, particularly where a critical combination of soil thickness and slope angle exists. In such areas, the usual triggering factor for landslides is the occurrence of heavy rainfall, generally at the end of the rainy season (De Vita, 2000). These landslides begin as debris slides. Downslope, they often evolve into debris avalanches, and then are transformed into debris flows that flow in stream channels and frequently reach the crests of the basal alluvial fans (Guadagno, 1991; Celico and Guadagno, 1998; Del Prete et al., 1998).

Chronicles of the 20th century reported the occurrence of these phenomena, chiefly when they caused property damage and loss of human life. Using these historical databases (Guzzetti et al., 1994; Calcaterra et al., 1999) it is possible to estimate within about 3 years the mean period of recurrence of landslides (De Vita, 2000). In order to achieve the comprehension of landslides triggering mechanism, many studies have been undertaken, generally oriented to conceptual modelling of the occasional formation of a perched water table in the surficial hydrogeological system (“pyroclastic soil-fractured carbonate bedrock”) during heavy rainfall and in discovering empirical rainfall thresholds for the triggering of debris slides (Celico et al., 1986, 2000; Celico and Guadagno, 1998; Fiorillo et al., 2001; De Vita and Piscopo, 2002).

On 5–6 May 1998, about one hundred debris flows struck the municipalities of Sarno, Quindici, Bracigliano, and Siano, located at the foot of the Sarno Mountains, causing the loss of 152 human lives. After this dramatic event research on debris flow hazard assessment increased rapidly, allowing new results and opening new scenarios in civil protection management, especially in the assessment of initial debris-slide susceptibility and in modelling debris-flow runoff.

Considering the slope instability process in this area, the thickness of pyroclastic soil and the slope angle appear to be the most important factors in instability of these types of landslides and therefore in landslide susceptibility assessment. Unfortunately, soil thickness surveying along the steep slopes of these carbonate mountains is difficult to carry out using traditional techniques, such as mechanised drilling, because of the absence of roads and the difficulty in carrying heavy equipment into the study area. Moreover, soil thickness, often up to 6 m, makes the use of light hand augers very time- and effort-consuming, and in many cases it is

impossible because boreholes collapse in the cohesionless lapilli strata. Instead, geophysical prospecting, even though providing only an indirect estimation of soil thickness, can be used easier on the steep slopes.

The aim of this study is the experimental use of the classic resistivity method in this particular geological context, combined with use of the refraction seismic method in thickness mapping of pyroclastic soils. As known these geophysical methods are usually applied in engineering geology practice to assess factors leading to instability of slopes as the thickness, water content or weathering grade of unstable, or potentially unstable, mass of soil or rock. In particular these methods can be used in the assessment of slope failure depth and for the reconstruction of landslide geometry, preferably in combination with test pits and boreholes (Bogoslovsky and Ogilvy, 1977; Johnson and DeGraff, 1988; Kelly and Mareš, 1993; McGuffey et al., 1996; Müller et al., 1986).

Finally, in order to model the distribution of soil thickness for landslide susceptibility assessment (Okimura, 1989; DeRose et al., 1991; Dietrich et al., 1995), we investigated the existence of an empirical model between pyroclastic soil depth and slope angle, since the thickness is conceptually controlled by the infinite slope limit-equilibrium model. These methods have been applied in a sample area, representative of a typical landslide-triggering zone.

2. Geology and description of the sample area

The geology and the geomorphology of the area are characteristic of the debris-flow-susceptible areas surrounding Mount Somma-Vesuvius. The area is located on the south-western slopes of Mount Pizzo d'Alvano (height: 1133 m a.s.l.) (Figs. 1 and 2), from which debris flows struck the town of Sarno on 5–6 May 1998.

Mount Pizzo d'Alvano belongs to the Sarno Mountains, a carbonate massif located at the south-eastern border of the Campanian Plain (Fig. 1), with about 60 km². The Mesozoic sedimentary sequence, which constitutes the carbonate bedrock of the massif, consists of limestone and dolomitic limestone. The morphology of the Sarno Mountains, generally steep, was mainly controlled by the Pleistocene extensional tectonic phases. Owing to these tectonic stresses, these mountains, as well as other carbonate massifs that surround the Campanian Plain subsided toward the centre of the Plain. In the central part of this structural depression, volcanic activity began from different eruptive centres: the Island of Ischia (150 ka to AD 1302), the Phlegraean

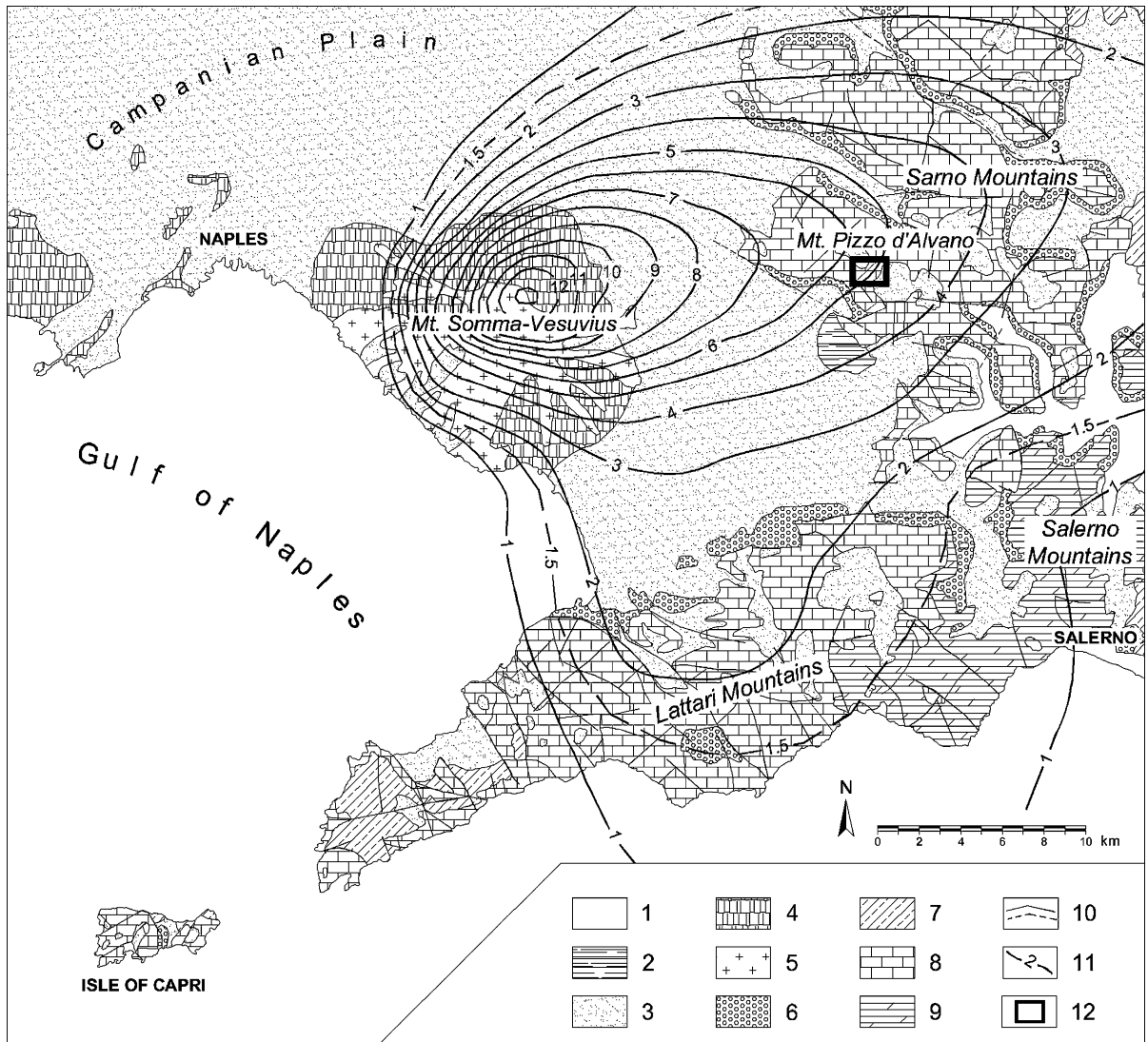


Fig. 1. Geologic map of the area around the Mount Somma-Vesuvius: (1) alluvial deposits; (2) travertine; (3) incoherent ash-fall deposits; (4) mainly coherent ash-flow deposits; (5) lavas; (6) detritus and slope talus deposits; (7) Mioocene flysch; (8) Middle Jurassic–Upper Cretaceous limestone; (9) Lower Triassic–Middle Jurassic dolomites and calcareous limestone; (10) outcropping and buried faults; (11) total isopachous lines (metres) of the most important of Mount Somma-Vesuvius eruptions (RPC: “Sarno” \Rightarrow 17 ka; “Ottaviano” \Rightarrow 8 ka; “Avellino” \Rightarrow 3.5 ka; AD 79; AD 472; AD 1631); (12) sample area (see Fig. 3).

Fields (39 ka to AD 1538) and the Somma-Vesuvius (25 ka to AD 1944). The volcanic and alluvial deposits filled the structural depression generating a wide flat area, the Campanian Plain, at the centre of which Mount Somma has risen (as the volcano was known at the time of the Romans). After the AD 79 and AD 472 eruptions, the volcano was transformed in Mount Somma-Vesuvius by the partial destruction of the original structure and by the superimposition of the Vesuvius’ volcanic cone (Fig. 1).

In the area of the western foot of the Sarno Mountains, a complete pyroclastic sequence has been recog-

nised, during which the most important volcanic events occurred in the Campanian Plain (Rolandi et al., 1998, 2000). The older pyroclastic products of this sequence constitute the “Ancient Pyroclastic Complex” (APC), which mainly consists of ash-flow deposits of the “Campanian Ignimbrite”, dated 39 ka. The younger pyroclastic products have been collected in the term “Recent Pyroclastic Complex” (RPC), which belongs mainly to the Mount Somma-Vesuvius explosive activity. Among the various eruptions, which constituted the “Recent Pyroclastic Complex” (RPC), the most important were the “Sarno”, “Ottaviano” and “Avellino” erup-

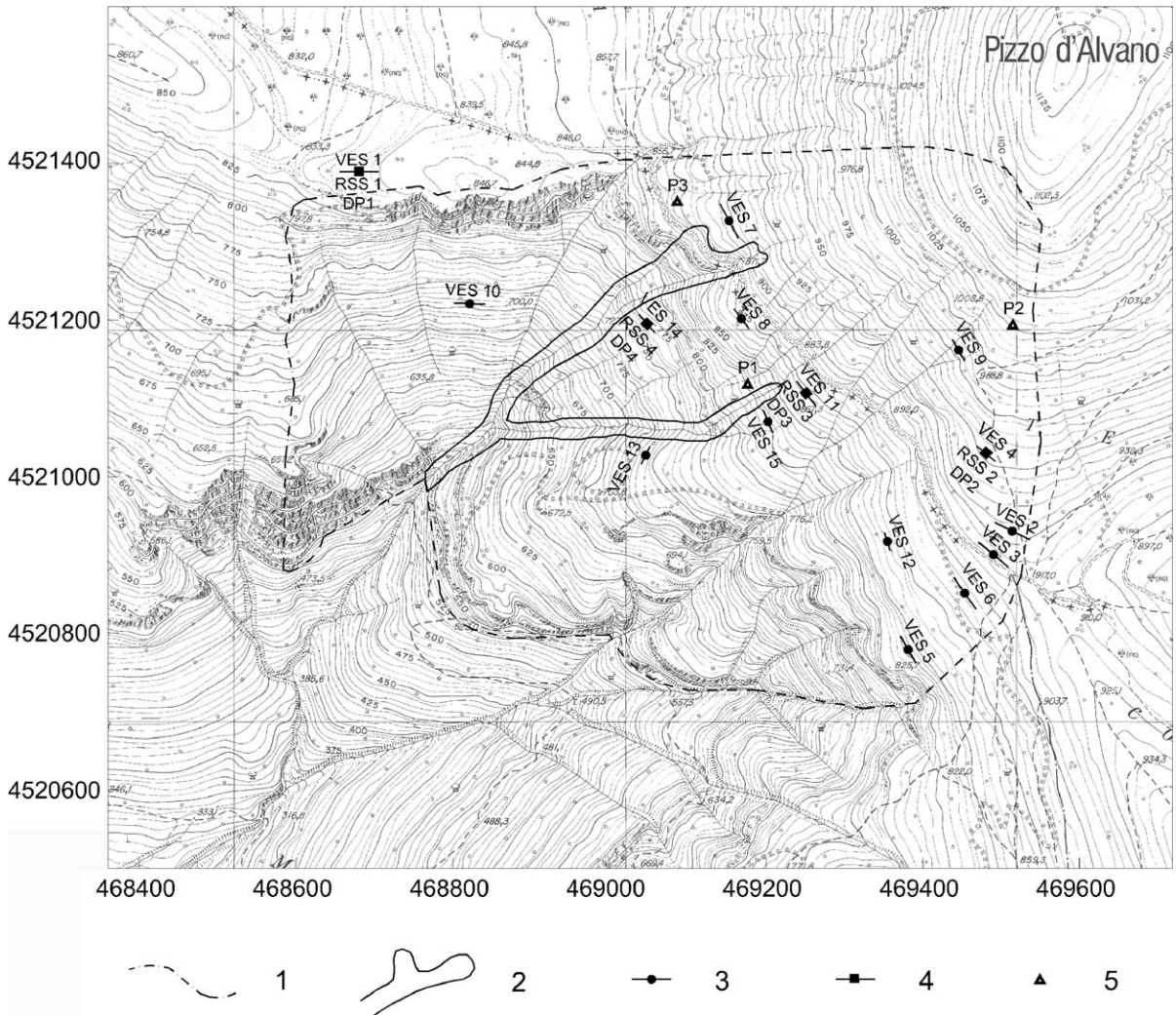


Fig. 2. Location of the soundings in the sample area: (1) sample area boundary; (2) 5–6 May 1998 debris flows; (3) location of vertical electrical soundings (VES); (4) location of combined vertical electrical soundings (VES), refraction seismic soundings (RSS), and dynamic penetrometer tests (DP); (5) location of test pits (P). The map is in UTM coordinates, 33 Fuse.

tions, which occurred, respectively, about 17 ka (Rolandi et al., 2000), 8 ka (Rolandi et al., 1993a) and 3.5 ka (Rolandi et al., 1993b), constituting the main source materials of the catastrophic debris flows of 5–6 May 1998. Instead, the pyroclastic deposits of the AD 79 (Lirer et al., 1973), AD 472 (Rolandi et al., 1998) and AD 1631 (Rosi et al., 1993) eruptions are poorly represented. The differing abundance of the various eruptive deposits surveyed at the western foot of the Sarno Mountains can be mainly related to the different orientations of the ash-fall dispersion axes, besides the total erupted volume. The dispersion axes were oriented mainly eastward, except for the AD 79 eruption, which was oriented southward.

In order to estimate the distribution of the ash-fall deposits of the RPC, a map showing total thickness has

been produced, by means of an algebraic sum of numeric grids, derived from the interpolation, with Kriging algorithm, of isopach maps, published for each eruption in the abovementioned papers. As it appears on the total RPC isopach map, the total thickness of ash-fall deposits fallen on the Sarno Mountains ranges from 4 to 7 m (Fig. 1); however, on the Lattari Mountains the total thickness is generally less than 2 m. Among the other information, from the total thickness isopach map, it has been possible to estimate the total volume of the ash-fall deposits of the RPC complex in about 5.9 km³ at least (computed on a surface of about 5000 km²).

The sample area represents a typical geologic and geomorphic situation in which debris-slides initiate (Figs. 1 and 2). This area, as well as the other debris-

flow source areas in the zone surrounding the Mount Somma-Vesuvius, is characterised generally by a concave, and in a few cases, rectilinear, steep slope close to the principal morphological divide. Along these slopes there is little evidence of drainage pattern; instead zero-order drainage basins, namely catchments without drainage channel (Dietrich et al., 1986), and one-order basins, with ephemeral channels, are the elementary watershed types most represented. This sparse hydrographic pattern can be related to, among the other factors, the relatively high permeability of the surficial pyroclastic deposits (De Vita and Piscopo, 2002), often higher than local heavy rainfall intensity, which can be estimated in about 1.9×10^{-3} cm/s or 67 mm/h to an altitude of 1000 m a.s.l. and with a return period of 100 years (Rossi and Villani, 1994). In these areas, generally located on the upper part of the slopes, a primary deposit of pyroclastic soils exists, reduced mainly by landslide phenomena. Moreover, in these areas it is possible to consider the secondary deposits due to landslide process as being negligible, both because the proximity to the morphological divide and because the high slope angle generally prevents the deposition of landslide materials.

In particular, the sample area is delimited at the upper boundary by the principal morphological divide and at the lower boundary by a series of sub-vertical

scarps related to differential erosion, in correspondence of very thick limestone strata (Fig. 2).

A geological survey of the sample area, conducted in artificial cuts, in the landslide scarps, and subordinately in three test pits (Fig. 3), allowed the distinction of a complex stratigraphy in the pyroclastic deposits, characterised by the overlapping of different eruptive deposits among which pedogenic processes developed. Therefore pedological classification of horizons has been applied to give a better comprehension of the depositional events (USDA, 1998; Terribile et al., 2000). In addition, geotechnical classification of horizons has been carried out by means of laboratory tests and the application of the Unified Soil Classification System (USCS). The stratigraphy can be generally sketched as follows: (1) A horizon, characterised by an abundance of humic organic matter, in which pumice fragments can be distinguished with difficulty, classified as highly organic soil (Pt) with the USCS; (2) B horizon, characterised by fine and coarse ash pumice deposits that are weathered, including an abundance of silt that formed by means of illuvial processes (USDA, 1998), classified as sand with silt (SM); (3) C horizon, namely “parent material”, consisting of scarcely weathered pumice, ranging from coarse ash to lapilli in grain size (Schmidt, 1981), classified as clean gravel and sand from well to poor graded (GW and GP); (4) Bb

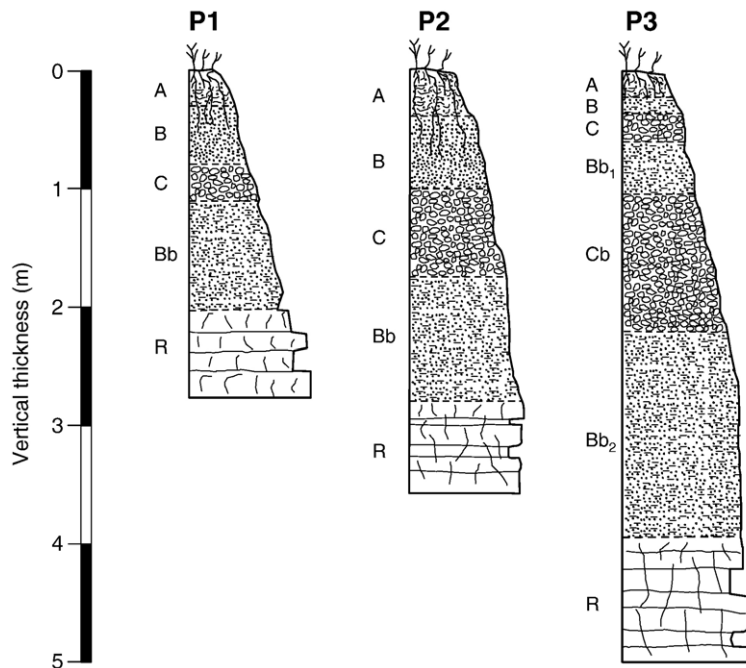


Fig. 3. Stratigraphic columns derived from test pits P1, P2 and P3. Pedological characterisations of horizons are showed (USDA, 1998), which have been geotechnically classified (USCS) as follows: A (Pt); B (SM); C (GW–GP); Bb (SM); Cb (GW–GP). R represents the fractured carbonate bedrock.

horizon consisting of strongly weathered fine ash deposits, representing B and subordinately A horizons buried by successive eruptive deposits (paleosoils), classified as sand with silt (SM); (5) Cb horizon consisting of scarcely weathered buried pumice, ranging from coarse ash to lapilli in grain size and classified similarly to C horizon (USCS); (6) R horizon, consisting of fractured carbonate bedrock with fractures filled by finer pyroclastic soil.

Obviously pyroclastic deposits after deposition underwent erosive processes along slopes, especially in areas with higher slope angle. It follows that in such depositional environment, pyroclastic series are often incomplete and stratigraphic correlations among deposits are difficult to carry out. The stratigraphic series consisting of A, B and C horizons can be referred to one of the most recent eruption of Mount Somma-Vesuvius and to the following pedogenic processes, while the Cb and Bb horizons can be correlated to an antecedent eruption of the Recent Pyroclastic Complex. Therefore the succession of depositional events is more complete when Bb and Cb horizons exist, as we found in P3 (Figs. 2 and 3). More complete pyroclastic series can be recognised in areas with gentler slope angle, whereas erosion and/or secondary deposition along the slope (due to landslide, talus or colluvial deposition) can be excluded. It appears reasonable that the presence of deposits of Ancient Pyroclastic Complex is negligible along the slopes because of the long duration of denudation processes since deposition.

3. Geophysical methods and criteria of application

We experimented with the resistivity method, using the quadripolar Schlumberger array, specifically designed for shallow soundings, with electrode spacing AB/2 up to 25.1 m, in some cases combined and matched with seismic-refraction and dynamic penetrometer data. The reliability of these methods in the geologic and morphologic situation examined is based on the following hypotheses: (i) pyroclastic soils can be distinguished from fractured carbonate bedrock by means of electrical resistivity and seismic velocity; (ii) the separation interface between pyroclastic soil and bedrock, as well as among pyroclastic horizons, can be considered approximately parallel to the slope surface in the short range of geophysical spacing; (iii) lateral discontinuities in the pyroclastic soil are negligible. According to these hypotheses, the estimation of soil thickness corresponds to the real thickness of pyroclastic soil (z), namely the depth measured perpen-

dicularly to the ground surface, because the electrical field and seismic wave fronts deepen forward to the bedrock interface, as occurs on a horizontally layered system. Moreover, soil thickness resulting from the application of geophysical methods obviously can be referred to a smoothed interface between pyroclastic mantle and bedrock.

In order to minimise lateral variations caused by a topographic effect, we carried out the electrical soundings on sectors of the slope that were approximately rectilinear, generally orienting the quadripolar array parallel to contour lines. Moreover, to achieve a detailed apparent resistivity curve, we measured nine points for each logarithmic decade.

The equipment used was light and portable, specifically designed for shallow soundings up to AB/2=25.1 m. It consists of a portable DC source (300 V DC, with a current up to 1000 mA) and receiving instruments represented by: amperometer (with a resolution of 10 μ A and a precision of $\pm 0.3\%$ in the range 0–200 mA), a voltmeter (with a resolution of 10 μ V and a precision of $\pm 0.05\%$ in the range 0–200 mV), and a spontaneous potential eliminator. Electrodes used were, as applied in common practice, made of stainless steel, for current electrodes (A and B), and made of copper, for the potential electrodes (M and N).

We executed 15 electrical soundings in the sample area (Fig. 4), where some of the initial debris slides occurred on 5–6 May 1998, in some slope sectors characterised by different mean slope angles, in the range 5–44° (Fig. 2). In order to obtain resistivity values of pyroclastic soil, not influenced by different water contents, the soundings were carried out during September 2001, at the end of the dry season, in a period without rainfall. Owing to the resistivity of the pyroclastic soil, the recorded voltage values were distributed in the range 50 mV to 10,000 mV, and the recorded current values in the range 10–100 mA, hence within the precision limits of the instruments.

The inversion of apparent resistivity data (ρ_a), as is known, is affected by a non-unique solution in terms of combinations between resistivity values and layer thickness. Therefore, the interpretation of soundings has been based on the calibration of resistivity values (ρ) on outcropping layers of pyroclastic soils exposed in various artificial cuts. Another constraint in the inversion of field data, and on the calibration of pyroclastic soil resistivity values, has been obtained, for four of the resistivity soundings, by means of the estimation of the whole pyroclastic-soil thickness using other methods. The alternative methods used were shallow refraction seismic soundings and data from the appli-

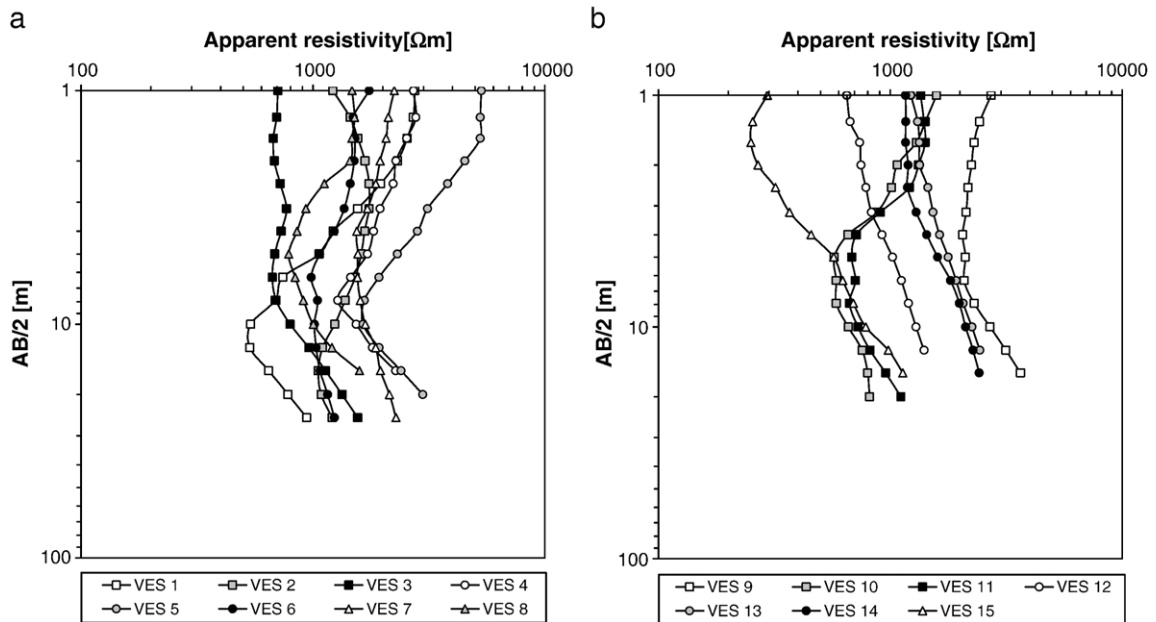


Fig. 4. Normalised apparent resistivity curves of vertical electrical soundings: (a) VES 1–8; (b) VES 9–15.

cation of a transportable dynamic penetrometer, used both only in favorable logistic situations because of the greater difficulty in transport.

Measurements of pyroclastic-soil resistivity obtained directly on the outcropping layers in artificial cuts and landslide scars indicated, for 10 determinations, a value of $1135 \pm 180 \Omega \text{ m}$ for the C horizon. This can be compared to a value of $190 \pm 50 \Omega \text{ m}$ for the Bb horizons. The different resistivity values for the same horizon show in the surveyed outcrops the difference in grain size and the different silt, and subordinately clay, contents of the soil layers. For this reason the previous measurements can be considered only partially representative of the resistivity variability in pyroclastic soils. It is important to put in evidence that resistivity values of pyroclastic soils are higher than the equivalent in grain size alluvial soils, owing to the high total porosity (up to 70%) that can be related both to intergranular and to intragranular voids of pumice clasts (Esposito and Guadagno, 1998).

The measured values have been matched with pyroclastic-soil resistivity values obtained from inversion of four resistivity soundings (VES 1, VES 4, VES 11 and VES 14), calculated fixing the thickness at the values derived from the inversion of refraction seismic sounding and from dynamic penetrometer data (Fig. 5). Obviously, the penetrometer data indicate the apparent thickness measured in the vertical dimension; therefore, these measurements have been adjusted, according to the slope angle, to estimate the soil thickness (z).

The number of resistivity layers has represented another fundamental variable in the geoelectrical data inversion. It has been constrained according to the local stratigraphic model, namely geological models derived from test pits (Fig. 3) and artificial cuts, as well as landslide scars, have been used to set out number of layers in the geoelectrical models and therefore to infer their stratigraphic characterisation. By means of this procedure, resolution limits of resistivity method have been put in evidence in some cases, especially in identifying surficial thin layers and/or layer with scarce resistivity contrast. In particular this problem has generally been verified in distinguishing A horizons from B horizons and, in a limited number of cases, from C horizons also (VES 3, VES 7 and VES 15); in all these cases the stratigraphic significances have been joined in the same resistivity layers (Fig. 6). Inversion of apparent resistivity curves has been made with IPI2Win v.2.1 software (Bobachev et al., 2001), calibrating resistivity soundings interpretation with the aforesaid constraints. All the interpretations reached a fitting error value less than 4%.

4. Results

4.1. Geophysical characterisation of the pyroclastic soils and the carbonate bedrock

The analysis of inversion of shallow resistivity and refraction seismic soundings characterises the different geophysical behaviours of pyroclastic soil and the car-

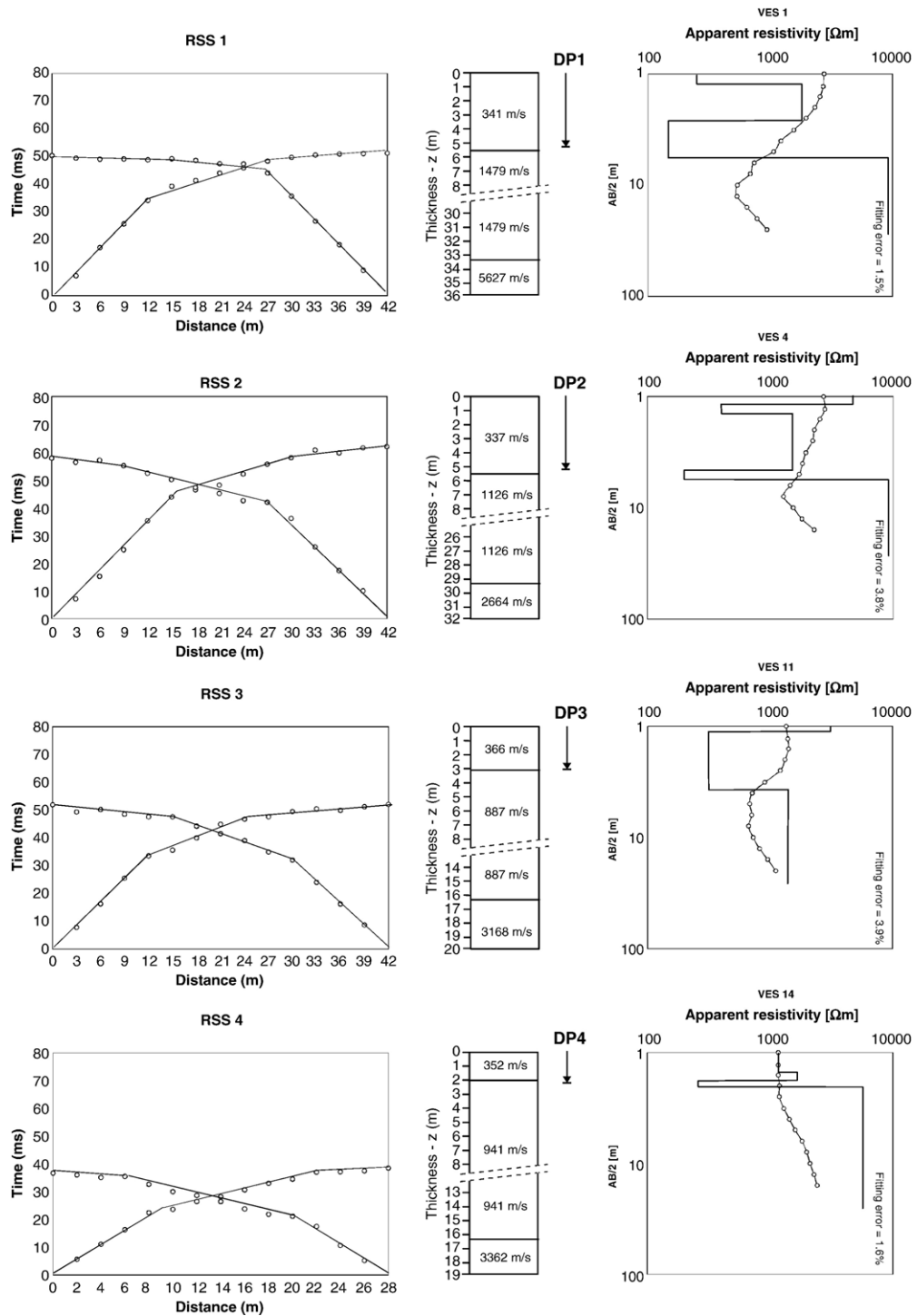


Fig. 5. Comparison between refraction seismic soundings (RSS), corresponding vertical electrical soundings (VES) and maximum depth of dynamic penetration tests (DP). Pyroclastic soil thickness derived from RSS inversions and DP data have been used to invert VES data.

bonate bedrock in terms of resistivity and seismic velocity, revealing information useful in geologic modeling and therefore for the interpretation of debris slide triggering conditions.

Except for the first apparent resistivity data, related to the A horizon, the resistivity curves approximately show a 3-layer H type shape (Keller and Frischknecht, 1966), with the central layer having the lowest resistiv-

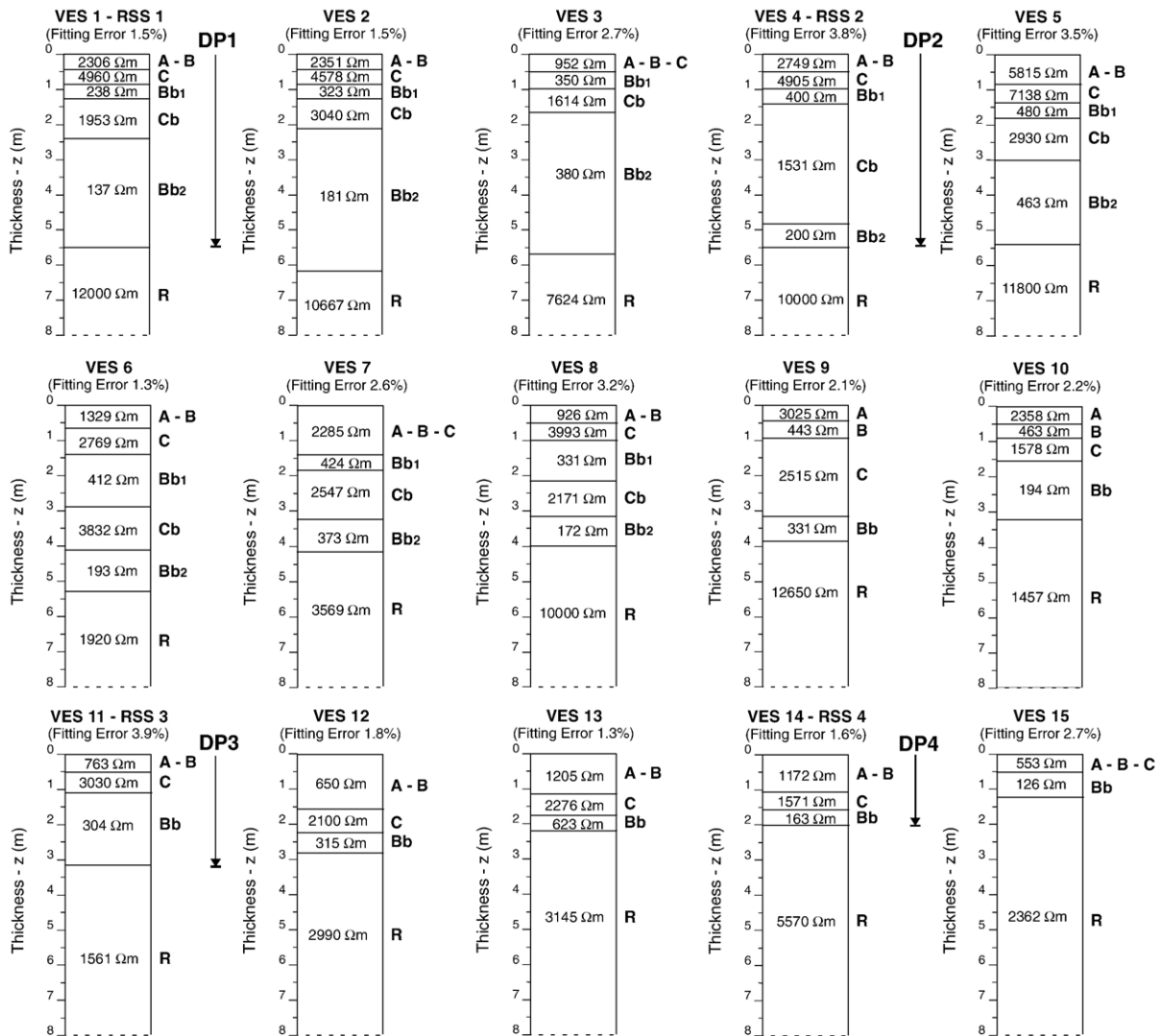


Fig. 6. Inversion results of vertical electrical soundings and correspondent stratigraphic interpretations. The maximum penetration depths of dynamic penetration tests are also shown.

ity value. This layer of minimum resistivity divides the resistivity curves into two parts, the first belonging properly to the pyroclastic overburden, the second to the carbonate bedrock (Fig. 4).

This minimum resistivity can be justified by the existence, as it appeared in some of the artificial and natural cuts that reached bedrock, as well as test pits (Fig. 3), of a basal layer represented by Bb horizon, mainly consisting of strongly weathered fine-ash deposits. This layer, always on the top of the bedrock and at the bottom of the ash-fall and lapilli deposits, appears to be affected by illuviation process (USDA, 1998; Terribile et al., 2000), which contributes to decreasing the resistivity of this layer by means of finer material coming from the upper horizon.

The paleosol basal layer allows the distinction in the apparent resistivity curves of the C or Cb horizons from the carbonate bedrock (Fig. 3); otherwise, it would be difficult to succeed in this separation. In fact, from the inversion results (Fig. 6), the carbonate bedrock exhibits resistivity values ranging from $1457\ \Omega\text{m}$ to $12,650\ \Omega\text{m}$, which partially overlap, especially on a logarithmic scale, with the resistivity values of the pyroclastic soils, ranging from $137\ \Omega\text{m}$ to $7138\ \Omega\text{m}$. The lowest resistivity values of the carbonate bedrock can be justified by means of higher fracturing grade of the rock mass and by filling of fractures with the finer pyroclastic soil, coming from Bb horizon. Instead the high variability of pyroclastic soils resistivity can be attributed to the different grain

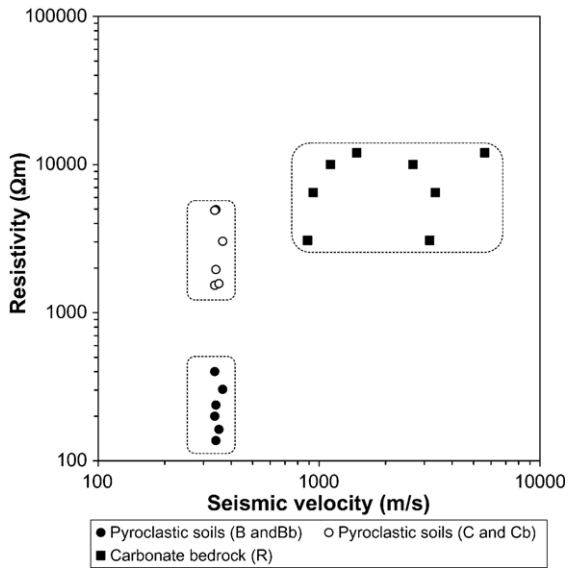


Fig. 7. Distinction of pyroclastic soil (B–Bb and C–Cb horizons) from carbonate bedrock (R) by longitudinal-wave seismic velocity and electrical resistivity values derived from combined VES and RSS soundings (VES 1-RSS 1; VES 4-RSS 2; VES 11-RSS 3; VES 14-RSS 4).

sizes, ranging from fine ash to lapilli that we found up to 2 cm in mean grain size.

The distinction on a geophysical basis between pyroclastic soils and carbonate bedrock can be clarified by

combining the resistivity values with seismic velocity (Fig. 7), derived from the refraction seismic soundings. This kind of elaboration allows a more complete geophysical characterisation of the “pyroclastic soil-fractured carbonate bedrock” system. In fact, even though the resistivities of the C and Cb horizons and carbonate bedrock can be reach comparable values, the seismic velocities are respectively very different being very low for pyroclastic soils (337–366 m/s) owing to the scarce compaction and the low bulk density of the deposits. However, even if the refraction seismic soundings could be considered more suitable in estimating the pyroclastic soil thickness, the lack in differentiation among pyroclastic series makes resistivity soundings more useful in this specific topic, besides the easier transportability of the geoelectrical equipment.

4.2. Distribution of pyroclastic soils in the sample area

The thickness of the pyroclastic soils, according to the original ash-fall deposit and a slope stability model, can be conceptually related to the slope angle of an infinite slope. In fact, the primary ash-fall deposit mechanism generally caused a distribution of pyroclastic soil with a thickness inversely related to the slope angle, owing to a distribution of the same vertical ash-fall flux on a slope surface that increases with the slope

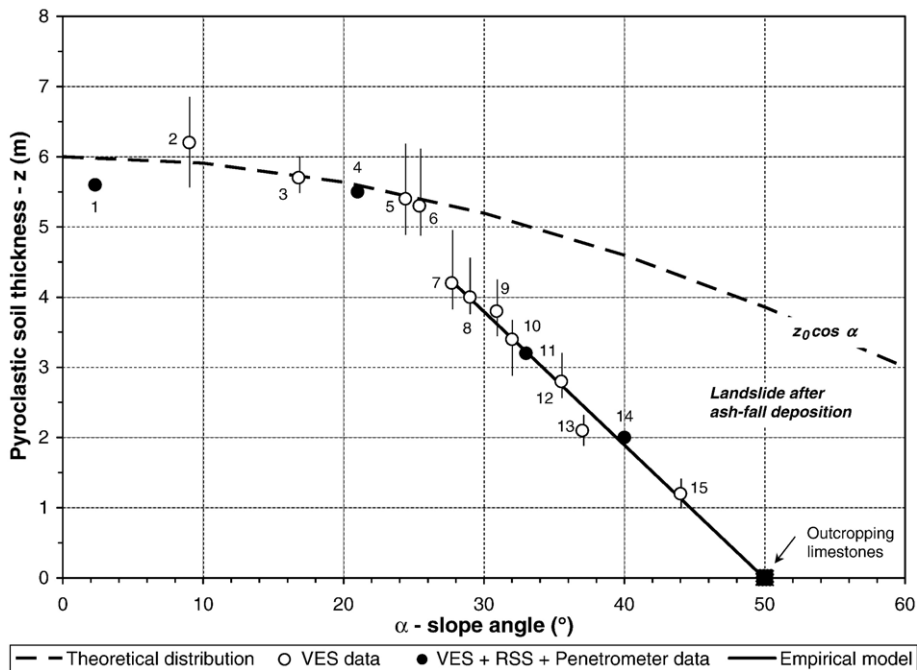


Fig. 8. Empirical model between pyroclastic soil thickness (z) and mean slope angle (α) in the areas in which resistivity soundings have been conducted. In this graph the theoretical distribution of ash-fall deposits with the slope angle is also shown, with $z_0 = 6$ m, as it has approximately been recognised in the Torriello area (VES 1-RSS 1-DP1). Vertical bars represent the pyroclastic soil thickness derived from equivalent geoelectrical models.

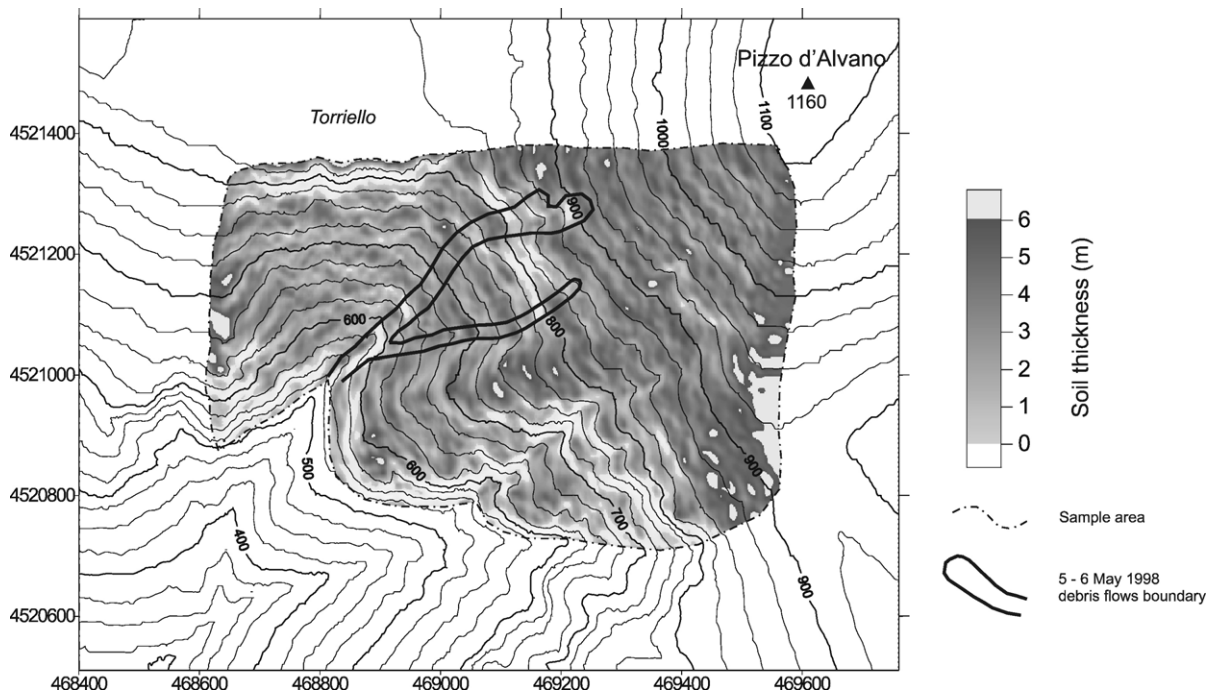


Fig. 9. Pyroclastic soil thickness map in the sample area, from which some debris-flows initiated on 5–6 May 1998. The map is in UTM coordinates, 33 Fuse.

angle. Therefore, assuming z_0 as the total ash-fall depth fallen on a horizontal surface, the ash-fall thickness, z , fallen on a slope, with α as the slope angle, is obviously given by $z = z_0 \cos \alpha$. Immediately after deposition, the pyroclastic deposits were affected by global instability, controlled by the equilibrium between driving forces and the shear strength of soils, which equilibrated the pyroclastic soil thickness with the slope angle, close to the limit equilibrium under ordinary hydrological conditions. Many traces of ancient debris flows have been found in the deposits which overlie and often intercalate the eruption deposits at the foot of the Sarno Mountains (Rolandi et al., 2000). Obviously, plant roots can contribute to the stability of the pyroclastic soils, but generally the roots don't reach the carbonate bedrock, thus limiting their stabilising effects to the surficial part (A and B horizons) only and not crossing lapilli strata (C horizon). Thus, at present, the stability condition of the pyroclastic overburdens has not yet been satisfied, especially during rare hydrological events represented by very heavy rainfall, occurring at the end of the rainy season and in the zone where artificial cuts or natural interruptions of the pyroclastic soil mantle exist (Celico and Guadagno, 1998).

The existence of an empirical relationship between ash-fall soil thickness and slope angle appears to be an

acceptable hypothesis in a homogenous slope area, located in the proximity of the morphological divide, in which a primary ash-fall deposit exists. In fact, under these conditions due to the slope angle, the relatively high permeability of ash-fall deposits and the wooded vegetation, the erosional processes acted by runoff can be considered subordinate respect to erosion due to landslide phenomena and limited to the areas with scarce vegetation.

According to the aforesaid concepts, the empirical relationship between pyroclastic soil thickness, estimated with the geophysical resistivity soundings, and the mean slope angle of the sounding areas has been verified. In this relationship, besides the data from resistivity soundings (Fig. 6), observations of aerial photographs and field survey data for the zones without pyroclastic overburden have also been considered, generally indicating the absence of pyroclastic soils for slope angles greater than 50° .

In order to verify the original total thickness of ash-fall soils on the sample area derived from the various eruptions of Mount Somma-Vesuvius, the pyroclastic soil thickness on a gentle sloping morphological divide, separating the south-eastern steep slope of Mount Pizzo d'Alvano from the Torriello tectono-karstic depression, has been estimated. This area can be considered con-

servative regarding the original total thickness of ash-fall deposit because local morphological conditions prevented significant losses due to erosive processes and deposition due to landslides. Resistivity, refraction seismic soundings and dynamic penetrometer tests (VES 1-RSS 1-DP1) have been carried out (Figs. 2 and 5) in this area, estimating a total thickness of pyroclastic soil of about 5.5 m, which approximately corresponds to the value included within the isopach lines of 5 and 6 m that crosses the north-eastern sector of the sample area (Fig. 1).

The graphical correlation between estimated pyroclastic soil thickness and slope angle (Fig. 8) shows a good match between experimental data and theoretical model ($z = z_0 \cos \alpha$) up to a slope angle of 25° , assuming $z_0 = 6$ m as total thickness in the conservative areas. Instead, for a slope angle greater than this threshold value, soil thickness data diverge from the theoretical model, demonstrating the effects of denudation processes, mainly due to landslide phenomena. In the second slope angle range a simple linear regressive model, between pyroclastic soil thickness and slope angle has been found (z [m] = $-0.190\alpha + 9.5$) showing a strong reliability of the empirical relationship ($R^2 = 0.989$). Theoretical and empirical models appear to be sufficiently valid even if considering equivalent geoelectrical models within $\pm 0.2\%$ range of the fitting error values (Fig. 7), calculated with the informative-stochastic method (Goltsman, 1981) implemented in IPI2Win v.2.1 software.

This result allows the application of the model to the pyroclastic soil thickness mapping, even though this in an area, which is morphologically homogeneous and strictly inclusive of the area of sounding locations.

The empirical model, valid for the slope angle range of 25 – 50° , has been experimentally applied in the sample area to the slope angle data. These data have been derived from the elaboration of a 5×5 m resolution Digital Elevation Model calculated from a topographic map with 5-m interval contour lines (Figs. 2 and 9).

5. Conclusions

In this paper, classic geophysical methods in pyroclastic soil thickness mapping are proposed as alternative and applicable methods for the area of steep carbonate slopes surrounding Mount Somma-Vesuvius. In particular, the applicability of these methods owing to the geophysical properties of pyroclastic soils and of the bedrock has been demonstrated, putting in evidence the better suitability of geoelectrical methods

in characterizing and differentiating pyroclastic series, which are spatially variable along the slopes. This capability of the resistivity method appears in a few cases limited by thickness and resistivity contrasts among pyroclastic layers, but generally it can be considered reliable. In fact, the analysed apparent resistivity curves have generally shown inversion models compatible both with the local geological model and approximately with the resistivity ranges derived from direct measurements. Therefore the application of the aforesaid constraints has allowed a consistent estimation of the stratigraphic scheme and of the total pyroclastic-soil thickness, even if resolution limits have in some cases not allowed a detailed identification of thinner horizons.

Moreover, in this paper it is shown that geophysical methods can be used, as well as other methods applicable to steep slopes, to reconstruct empirical relationships between pyroclastic soil thickness and slope angle. In particular, it is important to note that the soil thickness along the examined slopes is distributed inversely to the normal condition in which soil depth is formed by regolith alteration and downslope sediment transport. In fact, in the normal model soil depth is smallest on the morphological divide and generally increases downslope and especially in areas of hydrographic convergence (Dietrich et al., 1986, 1995). Instead in the studied case, the pyroclastic soil mantle is generally thicker at the morphological divides, whereas the slope angle is lower. The occasionally shallow depth of pyroclastic soils at the principal morphological divides, gives an exception for this distribution of pyroclastic soils, attributable to the scarce presence of wooded vegetation. In fact, this condition, often caused by deforestation and wildfire, provoked a rapid erosion of pyroclastic soil.

Implementation of an empirical model to a slope angle numeric map, applicability of the proposed model in pyroclastic soil thickness mapping, even if it is approximate and valid in the area in which soil thickness data were detected, have been demonstrated. These results can be considered significant; in fact, the soil thickness map has a basic importance in shallow landslide susceptibility modelling (Casadei et al., 2003). In particular, in an urbanised area as that surrounding Mount Somma-Vesuvius, the proposed survey and elaboration methods can be used to establish debris flow runout scenarios, providing an estimate of the pyroclastic soil volumes that can be moved during the occurrence of the landslides.

Among the results obtained, the constant presence of a relatively low resistivity layer overlying the bed-

rock, which can be related on the basis of the survey data to the Bb horizons that have originated from weathering and illuvial processes, has been put into evidence. This finding demonstrates chiefly the capability of the resistivity method to estimate the hydrogeological condition represented by a basal relatively low permeability layer that separates the very permeable C, or Cb, horizons from the fractured carbonate bedrock. This predisposing condition can favour the formation of a temporary perched water table, especially at the end of the rainy season when the soil is moister, with a critical effect on the stability of the pyroclastic mantle.

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