ANNALS OF GEOPHYSICS, VOL. 46, N. 6, December 2003

Geophysical surveying of slopes affected by debris flows: the case of S. Felice a Cancello (Caserta, Southern Italy)

Vittorio Chiessi ([1]), **Maurizio D'Orefice** ([1]) **and Sabino Superbo** ([2])
([1]) *Agenzia per la Protezione dell'Ambiente e per i Servizi Tacnici (APAT), Roma, Italy*
([2]) *ENEL HYDRO, Seriate (BG), Italy*

Abstract
This paper contains the results of a series of geophysical investigations carried out on the largest debris flow to have taken place in Tavernole, S. Felice a Cancello (Caserta, Southern Italy). The landslide occurred in concurrence with other catastrophic events in the Sarno Mountains in May 1998. This research project is part of a series of geological, geomorphological and geotechnical studies whose purpose is to improve the knowledge of this type of phenomenon. The project also tested and compared various survey methods in the sample area of S. Felice a Cancello. Geophysical surveying allowed us to collect information regarding the physical features and thickness of the materials affected by landslide phenomena and to verify the applicability and effectiveness of the various indirect surveying methods adopted. The preliminary results of the study enabled us to generate a series of suggestions which could prove useful in formulating the correct approach to this type of problem to be adopted in ordinary professional practice. These indications concerned the type of geophysical surveying to be conducted and, where applicable, the means of implementation. In general, seismic refraction was found to be the best technique for collecting information on the area studied.

Key words *debris flow – geophysical surveys – S. Felice a Cancello (Caserta, Southern Italy)*

1. Introduction

This paper is an integral part of a wider research project carried out by the Italian Geological Survey on areas affected by fast-moving debris flow phenomena following the 1998 disaster in Sarno (Chiessi *et al.*, 2000, 2002).

The project includes several geological, geomorphological and geotechnical studies on volcaniclastic deposits covering carbonate slopes. The purpose of the project is to improve the knowledge of this type of landslide phenomena and to characterize and standardize methodologies for extracting data. Where applicable, a full set of direct and indirect geognostic surveys were performed in a sample area (fig. 1) in order to establish a geotechnical model of the studied event. Stability analyses using different methods were also performed in order to assess the most suitable one for the purpose (Chiessi *et al.*, 2003).

This paper also presents certain aspects revealed by geophysical surveying in the sample area of S. Felice a Cancello (Caserta) in which a series of fast-moving debris flows were generated during the disaster of May 1998. Particular attention focused on the largest flow (fig. 2), which occurred in the Vigliotti area of Tavernole, on the western outskirts of the town of S. Felice a Cancello. The flow commenced on 5

Mailing address: Dr. Vittorio Chiessi, Agenzia per la Protezione dell'Ambiente e per i Servizi Tacnici (APAT), Via Curtatone 3, 00185 Roma, Italy; e-mail: vittorio.chiessi@apat.it

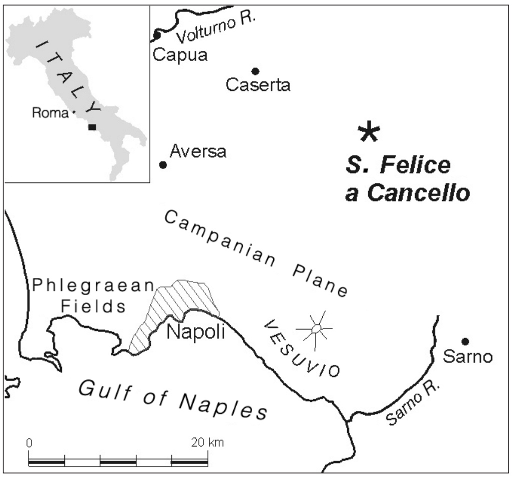

Fig. 1. Localization of the study area.

Fig. 2. Front view of the landslide of 5 May 1998 in the municipality of S. Felice a Cancello (Caserta, Southern Italy), in the Vigliotti district.

May 1998, following a not particularly heavy rainfall, and affected the northern slope of the hill from Mount S. Angelo Palomba (550 m a.s.l.) to the Castle of Cancello (207 m a.s.l.). The slide originated at a height of about 330 m a.s.l. and quickly moved down the valley involving the volcaniclastic sediments covering the carbonate substratum. Shortly before stopping in the flat toe of the slope area (about 70 m a.s.l.), the flow destroyed several specialized crops and an industrial warehouse. A neighbouring warehouse was also damaged. According to the latest data, the volume of debris carried by the slide can be estimated at around 60 000 m^3.

2. Geological and geomorphological aspects

The study area is part of the extreme western sector of a carbonate ridge of the Avella Mountains (Southern Apennines), close to the bounding Campania Plain. More specifically, it is bordered by the northern slope of the E-W ridge between Mt. S. Angelo Palomba and the Castle of Cancello (Caserta). This slope – which terminates in a series of (often rather steep) normal faults – is part of an essentially calcareous succession of carbonate platform facies; it is covered by mainly continuous, essentially Holocene, detrital-colluvial deposits of prevalently volcaniclastic composition.

The slide caused the total dislodgement of the surface deposits which covered the underlying carbonate substratum and thus permitted observation of the subsurface layer.

The exposed slope showed an emerging substratum composed of a whitish and hazel-coloured calcareous strata of the Lower Cretaceous age. The substratum was affected by a widespread and considerable structural warp caused by mainly NW-SE and E-W joints and shear planes. The first Apennine-oriented shear plane system was associated with a significant displacement which enabled identification of three structural blocks formed of recumbent, sub-horizontal and upright folds respectively starting from the highest.

In the middle-low sector of the surface from which the fast-moving debris flow was formed, the calcareous substratum was covered by two generations of slope breccia of different ages. The older rock arranged in seams and sills, mainly covered the central structural block, while the more recent rock – which consisted of well-cemented breccia with inclined stratification – was extensively present above the central and lower structural block.

The most recent breccias probably date back to the cold periods of the final Middle and Upper Pleistocene age.

The carbonate substratum and the second generation slope breccias (where present) were covered by essentially recent detrital-colluvial sediments, composed of reworked volcaniclastic material, carbonate clasts and by Late-Quaternary pyroclastic deposits in primary folds. The latter were generally found in the middle-high part of the slope, while the reworked pyroclasts were found mainly at the foot of the slope in gullies and morphological depressions.

From the granulometric point of view, the detrital-colluvial sediments present variable distributions from sandy silt with clay to slightly gravelly sand, whose elements are generally composed of ash, lapilli and to a small extent by rough carbonate clasts. The latter's frequency increases towards the base of the deposit, where even elements of the dimension of the block are found. These deposits are frequently formed by soil-genesis and the carbonate clasts dispersed within them are often characterised by superficial whitish alteration patinas.

The pyroclasts in place consist of distal fall deposits, ascribable, according to Di Vito (personal communication), to the Campi Flegrei eruption of Agnano Monte Spina (4.4 kyr BP: Rosi and Sbrana, 1987; Orsi, 1997 – 4.1 kyr BP: De Vita *et al.*, 1999) and to the Vesuvius eruption of Avellino (3.8 kyr BP: Lirer *et al.*, 1973; Santacroce, 1987; Rolandi *et al.*, 1993; Cioni *et al.*, 1999a, 2000 – 3.4 kyr BP: Cioni *et al.*, 1999b).

These pyroclasts, composed for the most part of alternating inclined beds, formed of pumice lapilli and cinders, are found in alternation with ochreous paleosols.

In the plane opposite the foot of the mountainside, near the slopes of certain open-pit quarries, about 3 m below the countryside-plane, there are thick deposits of pyroclastic flows belonging to the Ignimbrite Campana (Barberi *et al.*, 1978; Rosi and Sbrana, 1987; Fisher *et al.*, 1993; Civetta *et al.,* 1997), lithified into subhorizontal folds, which are connected to the huge eruption of the Campi Flegrei, occurring, according to De Vivo *et al.* (2001), around 39 kyr.

From the geomorphological point of view, the slide originated on a regular, roughly straight, transverse-profile calcareous mountainside, with an average slope of around 35°.

Three zones with diverse morphological characteristics – a trigger zone, a transport zone and a deposit zone – were identified within the landslide area.

The first zone is situated on the higher part of the slope, at a height of about 330 m, and has an average slope of more than 45°. From this zone the flow propagated towards the valley with growing speed, totally dislodging the surface deposits which covered the underlying carbonate substratum.

The trigger very probably was a small landslide with a roto-translational movement, which involved a volume of material of a few cubic meters. This phenomenon occurred near the edge of a small, thickly-wooded, morphological drop, possibly resulting from ancient agricultural terracing. The presence of this morphological element, together with the fact that in this zone steep slopes and superficial deposits of about 2 m in thickness coexist below the above-mentioned morphological discontinuity, can be considered to be one of the predisposing causes of the first sliding movement.

This initial movement later degenerated into a much larger second movement of the fast-moving debris flow type.

In the transport zone, characterized by slopes varying between 40° and 5°, the propagation of the debris flow towards the valley carried growing amounts of volcaniclastic material and covered an increasingly large surface (avalanche effect), giving rise in this way to a form of erosion of the typical, isosceles-triangle, planimentric geometry (Montella, 1841; Ranieri, 1841; Lazzari, 1954; Mele and Del Prete, 1999). The flow in any case developed on an open mountainside without side restrictions. The lower sector of the transport zone was not affected by significant changes of the pre-existing topography, nor by obvious erosion surfaces.

In the deposit zone, which corresponds to the base of the piedmont strip, where the slopes are of between 5° and 2°, the debris flow started to slow down and deposit massive and heterogeneous material (diamicton) consisting of carbonate clasts with mainly silt-sand support, to a thickness of about 1.4 m.

3. Indirect surveys

3.1. *Surveys carried out*

The methods of indirect surveying used were:

– Seismic refraction survey;
– Dipole-dipole geo-electrical survey with imaging of resistivity measurements;
– SASW (Spectral Analysis of Surface Waves) survey;
– GPR (Ground Penetrating Radar) survey;
– Down-hole survey.

In placing the profiles and survey points we have tried, as far as possible, to have the various kinds of survey coincide in order to better compare results and thus assess the effectiveness of the individual methods adopted.

The positions of profiles and survey points are given in fig. 3.

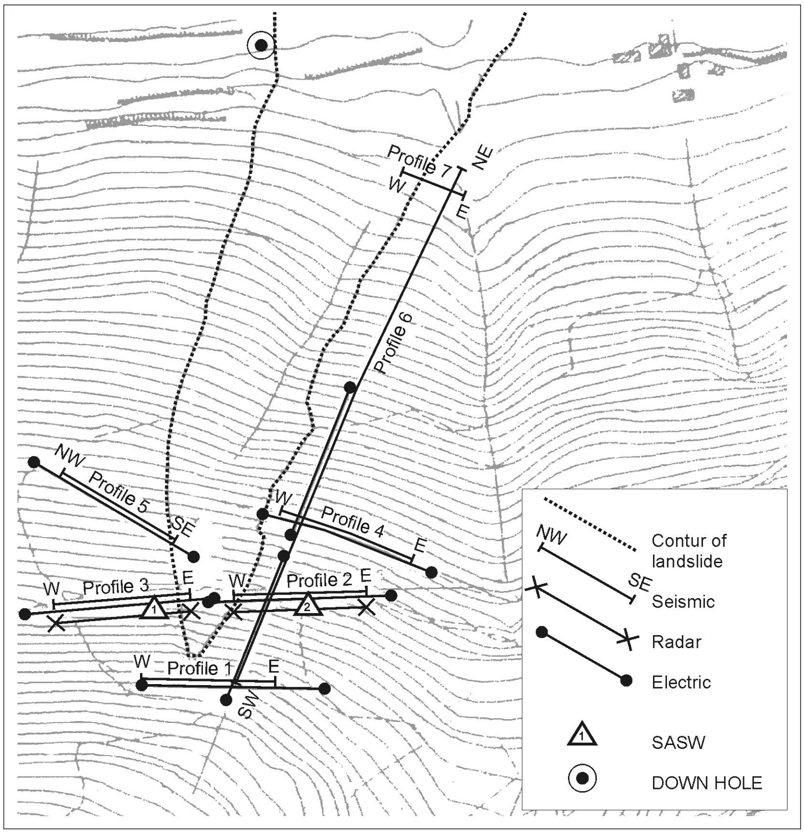

Fig. 3. Planimetry showing the positions of different indirect surveys.

3.2. *Seismic refraction survey*

3.2.1. Technical and instrument specifications for the survey

In the area examined the seismic surveys were performed along 7 alignments (seismic profiles) for a total length of about 970 m (fig. 3).

The surveys were carried out by laying out 24 geophones for measurement, placed at intervals of 4 m from each other. For each stretch, generally, the seismic signals generated in at least 5 energization points were recorded. An exception was profile 7, which was shorter and involved 12 geophones with 4 energization points.

The reception and recording of seismic signals was carried out respectively with Mark-L40a geophones with their own 40 Hz frequency and with a Byson-Mod. Jupiter seismograph equipped with a 21 bit analog-digital converter.

In order to energize the soil, a Betsy-Seisgun was used with blank cartridges loaded with 20 g of explosive powder.

The readings of the length of seismic signals and the processing of the dromochrones were carried out using Interpex Limited Firstpix and Gremix programmes respectively.

3.2.2. Survey results

The results of the refraction survey are shown in fig. 4. In each box, corresponding to the 11 stretches surveyed at 7 seismic profiles (see planimetry in fig. 3), the relative interpretative seismic sections with the indication of the velocity of the various strata are shown.

The geoseismic sections show a superficial layer, comprising continental deposits and characterised by seismic velocity values between 0.4 km/s and 1.0 km/s and with thicknesses varying between 2.0 m and 13.0 m. The minimum thicknesses of the cover are identified in the higher zone and on the western side of the slope, while the maximum thicknesses are found in the lower part.

As regards seismic velocity in the superficial sediments, the most realistic values are those of 0.4-0.5 km/s, recorded in the zones of greater thickness. The higher velocities, about 1.0 km/s, recorded in the zones of minimum cover thickness, can be influenced by refractive effects, as they can only be obtained using one, or maximum two, geophones. Therefore these values can appear higher than they actually are, even if from the point of view of interpretation everything is formally correct.

In order to correctly determine the velocity of the cover in these zones, it would have been necessary to reduce the distance between the geophones to about 1.0 m. In any case, the velocity values used to determine the substratum's pattern are not such that they significantly invalidate the thickness data for the geo-seismic sections.

The calcareous substratum and the stratified slope breccias, where present, are characterised by velocity values varying between 1.5 and 2.4 km/s. This difference is probably linked to variations in the characteristics of the material and its different degrees of alteration and fracturing.

3.3. *Geo-electrical survey*

3.3.1. Technical and instrument specifications of the survey

In the area examined, geo-electric surveys were carried out along 6 survey profiles for an overall length of about 870 m. The position of the electric imaging profiles practically coincides with those of the refraction survey, with the exception of the lower part of profile 6 and profile 7 (fig. 3).

Resistivity measurements were taken using the «Georesistivimetro» IRIS (Instruments)-Mod. SYSCAL R2, equipped with compensation system for spontaneous potentials and with a multi-electrode system for automatic data acquisition.

The adoption of a 32 electrode device with 4.0 m *e*-spacing for surveying led to the acquisition of 476 resistivity values for each measurement section, with an average resolution of 2 m.

The data obtained were then processed using M.H. Loke RES2DINV software; the inversion procedure used by the programme is based on the smoothness-constrained least-squares method

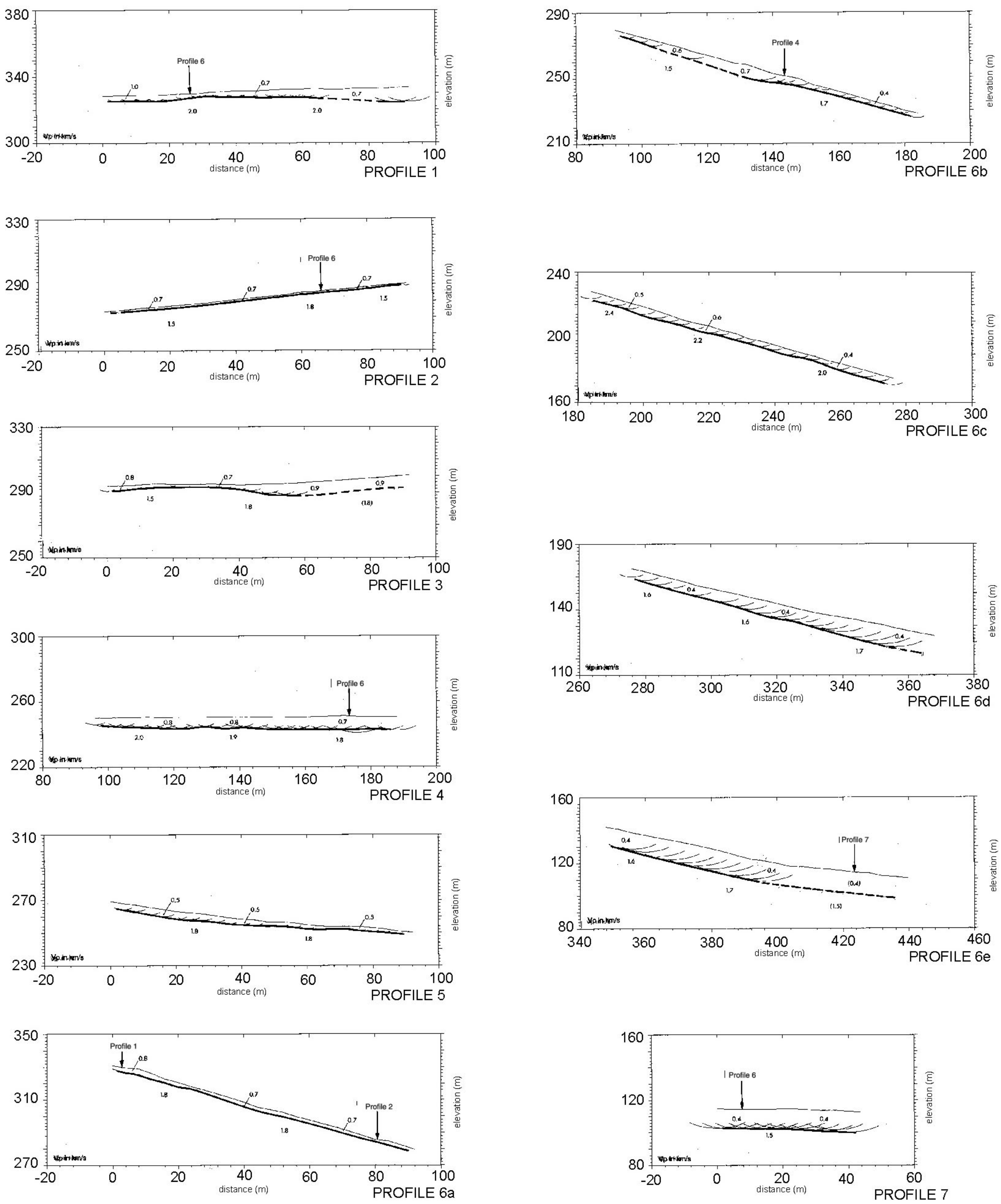

Fig. 4. Seismic refraction profile.

(de Groot-Hedlin and Constable, 1990; Sasaki, 1992) and has been universally recognized as the standard imaging processing method for over 10 years. The new implementation of this method uses the quasi-Newton technical optimization (Loke and Barker, 1996).

3.3.2. Survey results

From the analysis of the imaging sections processed, shown in fig. 5, a high variability of resistivity values can be observed, and it is objectively difficult to identify the boundary between the superficial deposits and the substratum.

By comparing these results with those of the refraction survey, which conversely identify this boundary with a good degree of reliability, it is deduced that, in this case, the resistivity values of the loose continental sediments are strongly conditioned by their degree of porousness, humidity, alteration, etc.; consequently they cannot show clearly the

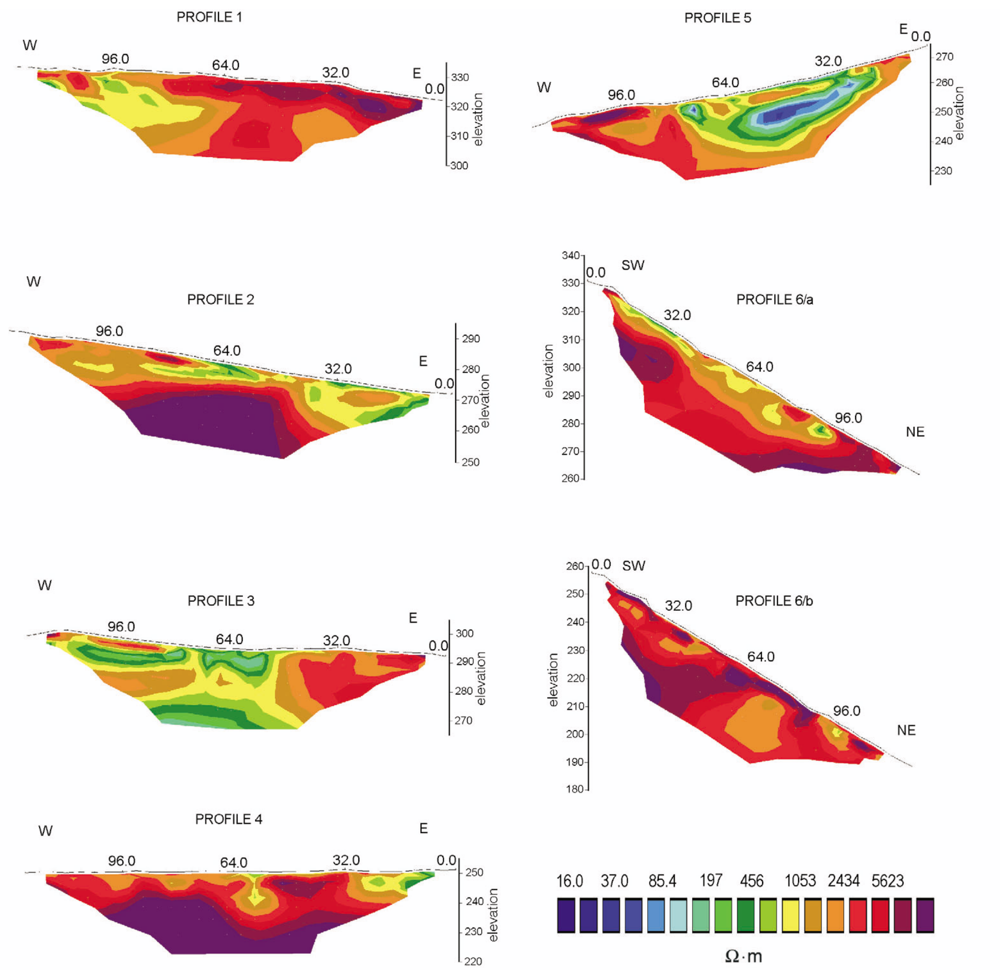

Fig. 5. Electric imaging profile.

passage between superficial deposits and the substratum.

Better results would have presumably been obtained if the distance between the electrodes had been significantly reduced to 1 or maximum 2 m. However, by using such a configuration, the costs, given the equal length of the area surveyed, would have been prohibitive; therefore a valid compromise was sought using a 4 m distance.

3.4. *SASW survey*

3.4.1. Survey technical and instrument specifications

In the area surveyed, the SASW method was applied along seismic profiles 2 and 3. The location of the tests is shown in fig. 3. The tests were carried out especially along two stretches of about 50 m each, using as a source of energy

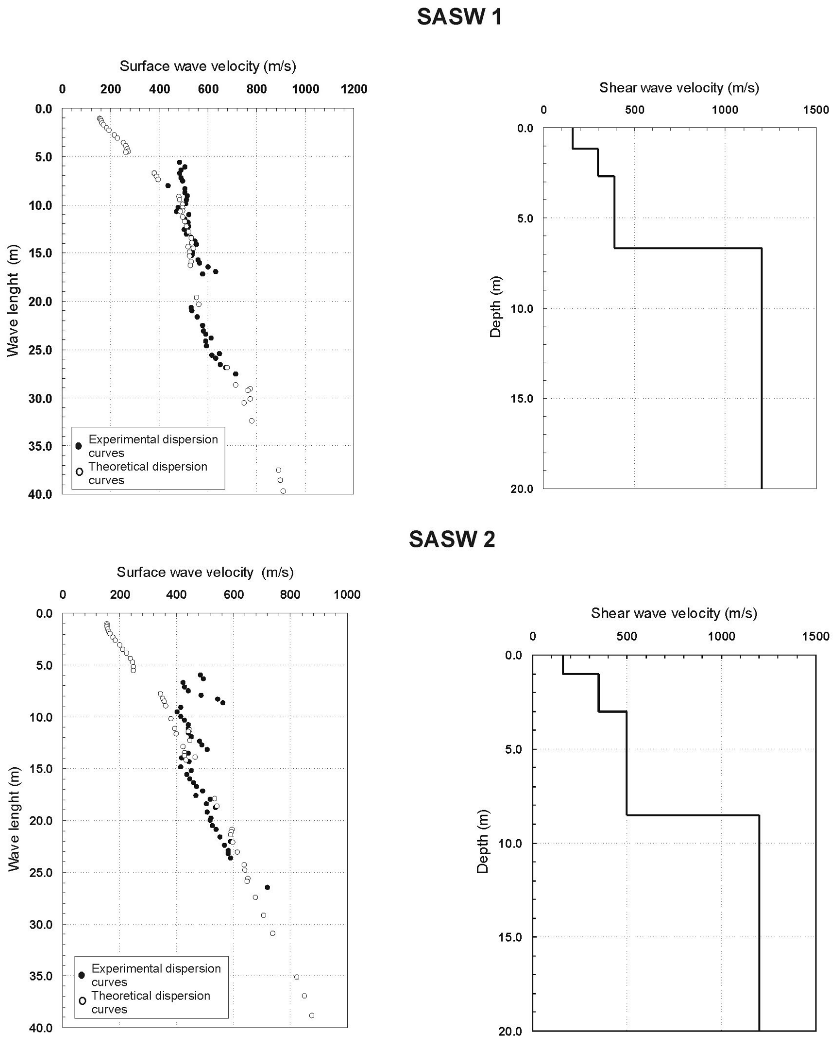

Fig. 6. SASW survey.

masses up to 50 kg; by operating in this way it was possible to survey the ground up to about 15 m in depth.

For the reception and recording of the signals, a pair of velocity transducers with natural frequency of 8 Hz and a dynamic signal analyser able to perform a spectrum analysis in real time (that is during the spot tests) of 2 signals detected in the time domain were used respectively. The sensitivity of the instrument is equal to 4 mV_p and the sampling frequency can be pushed up to 50 kHz per channel.

3.4.2. Survey results

The results of the two SASW tests, referring respectively to geophone 12 of profile 2 and to geophone 7 of profile 3, are shown in fig. 6 both as experimental and theoretical dispersion curves, and as diagrams of velocity of *S*-waves depending on depth.

In particular, the *S*-wave diagrams show a significant velocity change at about 3 m in depth, thus confirming what was recorded by the refraction survey both in terms of thickness and of velocity, naturally comparing the V_s velocity values with those of the relative V_p.

3.5. *GPR survey*

3.5.1. Survey technical and instrument specifications

In the area examined the GPR survey involved profiles 2 and 3, which were also surveyed with the seismic refraction method and the geo-electric method, for an overall length of about 180 m. The location of the survey plots is shown in fig. 3.

The surveys were carried out using the GSSI geophysical radar system SIR-10 with Mod. 3205-GSSI aerial and 300 MHz frequency centre.

Radar signals were collected with an analysis time (duration of recording of each signal) of 200 ns, which corresponds, considering a radar pulse velocity of about 8 ÷ 9 cm/ns, to a survey depth of about 8 ÷ 9 m.

The 300 MHz aerial was pulled by hand along the two profiles so as to acquire about 200 radar scans per each metre.

The signals recorded during the survey using the geo-radar system were then processed using GSSI RADAN software.

The main processing operations were:

– Application of vertical filters (in the time domain) and horizontal filters (in the space domain) to eliminate the interference with the signals.

– Normalization of signals with respect to distances, in such a way as to obtain a constant number of signals per unit of length.

– Representation of the signals with suitable colour scales, so as to highlight the most important and significant reflections.

3.5.2. Survey results

The results of the GPR survey are shown in fig. 7.

Even for this method similar considerations to those for the electric imaging can be made, as it is impossible to clearly identify the boundary between cover and substratum. Certain reflections are visible on the sections but, with the information in our possession, it is not possible to associate their position and their pattern to definite boundaries or structures.

3.6. *Down-hole survey*

3.6.1. Survey technical and instrument specifications

In the area examined the down-hole survey was carried out in the S.2 bore-hole to a depth of 10 m from the countryside-plane. The position of the test it shown in fig. 3.

Measurements were made using two vertical component Mark L-40a geophones, with their own frequency of 40 Hz. One of these was placed, fixed, on the surface, near the bore-hole mouth, to check the synchronism of signals, while the second was lowered gradually into the hole.

The energization of the soil, at a source-point at 4.2 m away from the bore-hole-mouth, and the

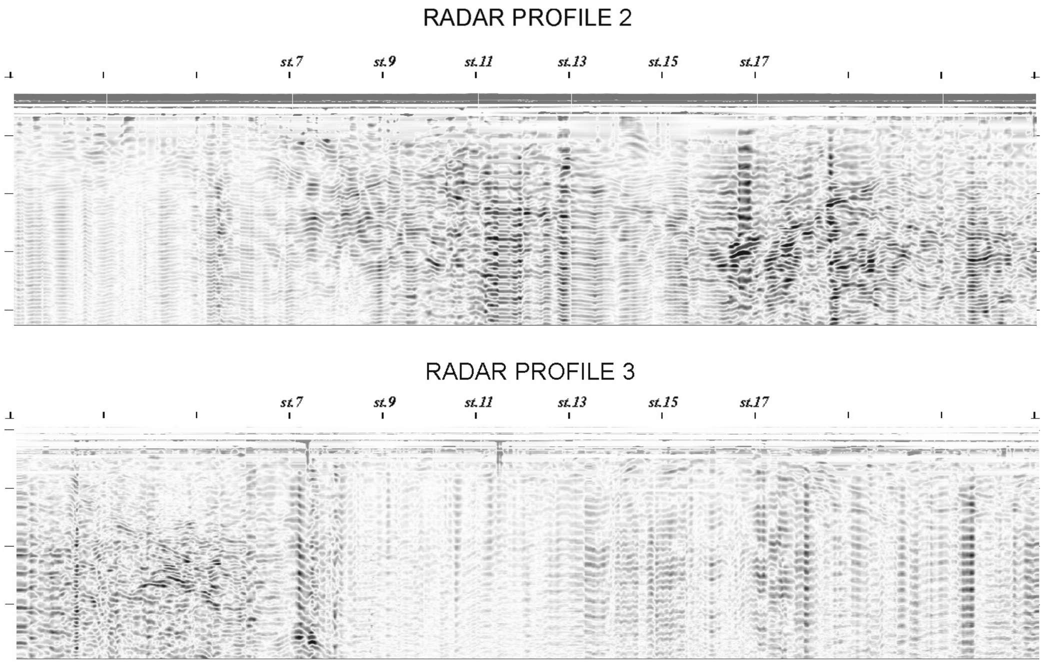

Fig. 7. GPR survey.

acquisition of the signals received by the two geophones were carried out using same equipment used for the refraction survey, that is:

– Betsy-Seisgun with blank cartridges loaded with 20 g of explosive powder;

– Byson-Mod. Jupiter seismograph with 21 bit analog-digital converter.

3.6.2. Survey results

The down-hole test was carried out inside the S2 test hole to a depth of 10 m, as the borehole cover was limited to that depth.

The results of the test are shown in the velocity diagram as a function of depth (fig. 8). This diagram shows that the ground perforated by the hole is characterised by average velocities of 0.37 and 0.8 km/s, that is, of the same order of magnitude of those determined through the refraction survey of the quaternary deposits.

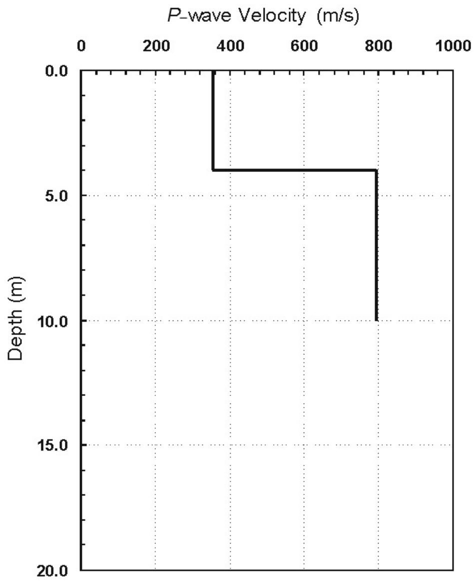

Fig. 8. Down-hole survey.

4. Conclusions

The indirect geognostic surveys carried out on the mountainside located in the municipality of S. Felice a Cancello (Caserta), which is affected by a gravitation phenomenon, allowed us to obtain information on the physical characteristics and thickness of the deposits affected by landslide phenomena, and to check the applicability and effectiveness of various methods of indirect surveying.

In this regard, the conclusions that can be drawn from the results obtained with the different techniques are, in principle, valid for lithological and morphological situations analogous to the one examined.

In general, the refraction method was able to provide the best information both in terms of detail and of data quality. From the processing of the seismic data it was possible to obtain the thickness of the loose superficial sediments and the velocity characteristics both of the superficial deposits itself and of the rocky substratum, which is formed by stratified calcareous rocks from the Lower Cretaceous and by breccia bodies of the mountainside with inclined stratification, which can be probably date back to the cold periods of the final Middle and Upper Pleistocene age. The thickness of materials obtained in this way agrees in large part with the data deriving from the several penetrometer tests carried out around the landslide area.

The results of the electric imaging survey, which was to be considered *a priori* to be an alternative to the seismic survey, and therefore was thought to be able to provide equally useful information, turned out to be less selective. In fact, from their analysis, it is not possible to clearly define the boundary between cover materials and substratum, as, very probably, the apparent resistivity values of the superficial sediments are of the same order of magnitude as those of the altered and fractured rock and, therefore, from the electrical point of view no net variation exists.

Electrical imaging was in any case important to confirm the variability of the characteristics of both the cover material and the substratum, a variability which is highlighted in the seismic survey by lateral variations in velocity within the same profile.

On the basis of these facts it is therefore possible to deduce that the rocky substratum is characterized by zones of more intense fracturing and/or alteration, alternated with more compact zones.

The other methods used – SASW, Georadar and Down-hole – gave results which substantially confirm those obtained using the seismic and geo-electrical surveys. However it should be noted that the former were shown to supplement the latter methods but, in the situation examined, would not have been conclusive if adopted alone.

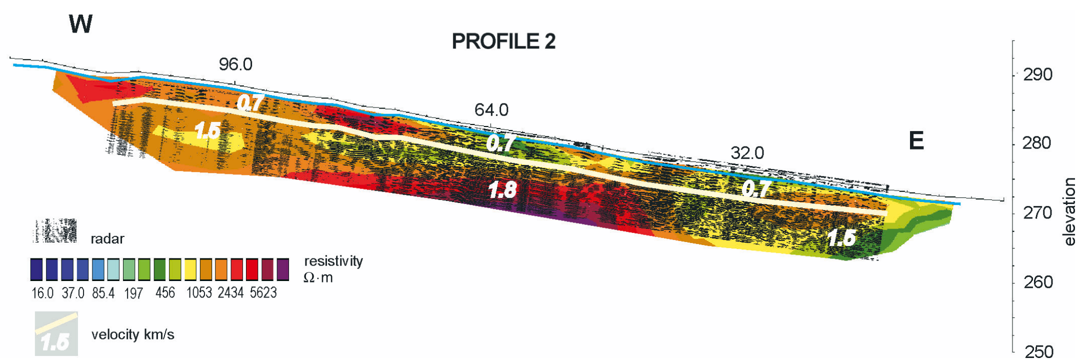

Fig. 9. Overlapping of three seismic, electric and radar methods.

More particularly, the SASW confirmed the depth of the boundary between the superficial deposits and the substratum in the surveyed zones, even if the quality of results suffered from the variability of the velocity and thickness characteristics in these zones.

As regards radar, wave penetration was strongly affected by resistivity variations in the materials, confirming that this technique is best used for dry materials with little resistivity, and cannot be employed indiscriminately.

The interpretation of radar prospecting was rather problematic as an excessive absorption of the signal took place. In general, there are no obvious reflection signals; the structure of the section, represented by the lithoid substratum, and of the overlying loose materials, is not evident.

In order to better characterize the surveyed section from the stratigraphic point of view, the use of an array of aerials with different working frequencies (*e.g.*, 200 MHz and 600 MHz, like in the case of the RIS/MF-Multifrequency system), undoubtedly appears to be more suitable.

The polarimetric data, then, can be used to deduce certain characteristics of the targets (*e.g.*, shape and direction), as well as to obtain information on the nature of the medium through which the radar signal propagates.

By way of example, fig. 9 shows details of the analyses carried out for sections 2 and 3 , in which there is an overlap of the three seismic, electric and radar methods. From the analysis of this figure, which shows two segments of 20 m each, it is evident that the various methods are not easily correlated; the reasons for this poor correspondence have been analysed above.

As regards the Down-hole, this proved useful to confirm the velocity values obtained with the seismic survey of the superficial deposits.

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(received May 15, 2003;
accepted November 10, 2003)