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GEOLOGICAL AND GEOPHYSICAL TESTS TO MODEL A SMALL LANDSLIDE IN THE LANGHE HILLS

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Abstract In April 2009, North-West Italy was interested by heavy rainfalls that triggered several landslides, especially of shallow type, and caused relevant rise of water level in many rivers, in some cases even beyond the alert level. Particularly in the hills near Alba (NW Italy), many landslides occurred, most of them belonging to the debris flow or soil slip types. In this area, a small but interesting landslide involved a local road and a high quality, recently planted, vineyard. The present study shows the use of different disciplinary approaches focused to understand the behaviour of this landslide: in particular, besides geological and geomorphologic studies, detailed topographic and geophysical surveys together with an in situ geotechnical/geomechanic characterization were applied. The combined interpretation of the different techniques and of field observations allowed to define a geological and technical model of the landslide, both in surface than in depth, that clarified the triggering mechanism of the landslide and allowed to perform a back analysis on both strength and pore pressure parameters.

Keywords heavy rainfall, heterogeneous rock masses, geophysical tests, landslide, Langhe, NW-Italy

Introduction

The study area is located in the southern Piedmont's hilly territory (Langhe), near Alba (fig. 1A). The geology is represented by sedimentary units mainly composed of terrigenous successions of interbedded layers of sandstone, marls and siltstone which are shaped with a typical "cuestas" morphology.

In this zone, between 26th and 28th April 2009 heavy rainfall, substantially exceeding the monthly values, were recorded (among 150 and 200 mm, which corresponds to about 25% of average annual rainfalls). Moreover, this event was anticipated by a particular rainy period: April 2009 was, in fact, the third rainiest month in the last century, and it followed a particular rainy and a very snowy winter too. For these reasons, a remarkable rise of water level in most of the rivers (especially Tanaro and Po Rivers) and the triggering of many landslides were observed. In this respect, Langhe hills are well known for their tendency to slide, especially with planar type movements (Cruden and Varnes, 1996), that mainly occurred on the gently dipping slope, and are very interesting for the very low angle of the sliding surfaces (Mandrone, 2004). On the contrary, steep slopes are mainly interested by surface phenomena connected to the movement of the covers, such as earth flows or rotational earth slides.

As it can be observed in fig. 1B, the study area is characterized by many recent landslides related to the mentioned rain event. The present study is focalized on a small failure, about 100 m long x 50 m wide, involving a road and a recently planted vineyard (fig. 1B). A multidisciplinary integrated approach (Chelli et al., 2006) has been adopted: topographic surveys, geophysical surveys and geotechnical characterization were combined to obtain a geological and technical model of the slope.

A common task in slope stability studies is to retrieve the internal structure and the mechanical properties of the soil characterizing the slope together with the groundwater circulation. It is indeed of major importance to determine the geometry of slope instability, particularly the position of the sliding surface, in order to facilitate reliable analyses and mitigation (Bruno and Marillier, 2000).

In many cases, the information on the depth and lateral continuity of the sliding surface cannot be obtained through boreholes (due to the cost of drilling) or geological investigations, as well as the identification of water distribution inside the slope. Geophysical techniques can be profitably used for this purpose. Satisfactory results in the investigation of landslides by means of a combination of geophysical and geotechnical techniques are reported by many authors (e.g. Mauritsch et al., 2000). Moreover, when shallow and small landslides are concerned, as in the present study, geophysical tests can be strongly cost effective in respect to other invasive methods. Best practice suggests that various (direct and indirect, surface and subsurface) methods should be used and cross checked to obtain more realistic results and best data to plan monitoring systems and mitigation.

In respect to geophysical techniques, water circulation paths or infiltration zones may successfully be delineated by electric resistivity methods (Bogoslovsky and Ogilvy, 1977; McCann and Forster, 1990; Hack, 2000). Moreover the limit between unstable weathered material and underlying stable bedrock is possible where they have different porosities and thus different resistivity values. The imaging of the electrical properties of the subsoil can thus provide information about the overburden thickness, the geometry of the sliding surface and the groundwater pathways (Godio and Bottino, 2001, Suzuki and Higashi, 2001). On the other hand, seismic methods can be used to infer the mechanical structure of the sliding body. Seismic refraction is particularly useful to detect discontinuities in the subsoil where strong contrast of seismic velocity have occurred between near surface degraded materials and stable bedrock. However, the low sensitivity to the solid skeleton properties in saturated soils, due to the influence of water on the P wave velocity, and the lack of resolution of surface refraction tomography affects the reliability of the P-waves analysis. In this respect, a combined acquisition of S-wave velocities will help in delineating a more complete framework (e.g. Jongmans et al., 2000).

Geophysical tests usually are not completely adequate alone, so the combined use with other geotechnical surveys (e.g. drillings or penetration tests, as in this study) will strongly help in confirming the uncertainties deriving from their evidence.

Geological and Morphological setting

The studied area (fig. 1A) belongs to the Tertiary Piedmont Basin (Gelati and Falletti, 1996). This sequence forms a gentle NW dipping uplifting structure, characterized by “cuestas” morphogenesis carried out by fluvial erosion. Indeed, the hills of the Langhe are characterized by asymmetrical slopes that range from 25° to 40° towards SW and from 10° to 25° towards NW.

This geological sequence is intersected by a series of faults mainly NE-SW and NW-SE trending. In some areas, these faults produced joints, sometimes very pervasive in surface. Most of the discontinuities are weathered due to water circulation; as an evidence of the high jointing level producing a surface water reservoir, the presence of many perpetual springs and shallow wells is noted (Mandrone, 2004). The drainage pattern is mainly controlled by morphology: main rivers cut deeply the landscape, according NE-SW faults trending, while most of the second-order streams mainly follow others geological structures in NW-SE direction.

Two geological formations characterize in detail the studied area (fig. 1B): the Diano d’Alba Sandstones Formation at the top of the hill, and the S. Agata Fossili Marls Formation, in the lower part of the slope. The former is represented by sand and sandstones dark-grey or yellowish coloured, some metres thick, interbedded to clayey-sandy marls, some decimetres thick. The latter is characterized by marls and clayey-marls, blue-grey coloured. These formations are usually considered as impermeable, but a remarkable water circulation takes place during heavy or prolonged rainfalls within the coarser levels and/or within the less cemented ones. The bedrock coverage is usually very thin (less than half meter) and characterized by silts and fine sands.

These geological structures are responsible for the tendency of the area to slide: last widespread events were during the flooding of November 1994 (Bottino et al., 2000). Furthermore, the landslides themselves create typical landforms that play an important role in their further development and reactivation.

Field Surveys

Topography and morphometry of the landslide

The landslide involved a concave slope dipping SW of about 20° which is cut by a road just at the bottom (fig. 2 and 3). After the event, a field survey was carried out on the area: preliminary surface observations pointed out two scarps, at the top of the landslide area, with height of about 1 m each. Using a total station, a more detailed topographic survey investigated the landslide and a significant area around it, allowing to define the morphometry after the failure. Georeferentiation was obtained using information from accurate location of ground control points during post-processing elaborations. These points (3 stations) were collected through a GPS device (dual frequency, dual-constellation RTK GPS, 24 GPS + 11 GLONASS Satellites with fully integrated receiver/antenna). Data elaboration was carried out by a GIS system to relate the collected data with the following digital thematic cartographies.

Water must have played an important role, as humidity traces were clearly visible for many days after the event in different parts of the landslide body, in particular in the central and in the lower part of the slide. Particular attention was paid to a wet area observed in the lower part of the slide, where evidence of liquefaction of the sandy levels was widespread.

The foot of the landslide over passed the road: it is represented by a debris flow of the displaced material. Luckily, a rural house located just a few meters below the road wasn’t affected by the landslide; all dismembered material lying on the road was immediately taken away to permit local traffic.

Just on the other side of the hill, a man made trench was observed (fig. 3). This trench acts as agricultural channel and collects water from houses and fields located to the E of the study area; due to the abundant rainfalls of the days immediately before the sliding, it should be almost full when the slope failed.

Geological/geomechanic characterization

The outcropping geological formations are characterized by alternations of sands (differently cemented) and clays or claystones. They are generally subjected to quick meteoric weathering when outcropping. According to the mechanical classification proposed by Marinos and Hoek (2001), the Arenarie di Diano d'Alba Formation represents a heterogeneous rock mass, belonging to the C type, with a GSI (Hoek & Brown, 1997) equal to 35. Furthermore, this complex shows low-quality geomechanical properties, with the uniaxial compressive strength of the intact rock elements (σ_{ci}) of about to 5 MPa and m_i (constant defining the frictional characteristics of mineral components in the rock elements) of 10 (Mandrone, 2006).

The Marne di S.Agata Fossili Formation outcrops in a lower position: mostly made up of silts and clayey-silts belonging to Flysh type G (undisturbed silty or clayey shale with or without few very thin sandstone layers), and can be also reference as weak, heterogeneous rock masses (WH type; σ_{ci} = 2 MPa, m_i = 7). This formation is deeply influenced by degree of saturation, showing a brittle to ductile transition at low lithostatic pressure. In respect to water circulation, this formation may be considered almost impermeable.

From an hydrogeological point of view, a remarkable water circulation takes place within the coarser levels and/or within those less cemented, or along the more open jounts of faults.

Geotechnical characterization

Geotechnical surveys were done some days after the landslide event. For in situ surveys, a light dynamic penetrometer was used with 30 kg weight hammer falling from a height of 20 cm. Three tests (PP1, PP2 and PP3) were carried out in the central part of the main body of the landslide, along a line also used for geophysical surveys (fig. 2), in order to verify the state of the subsoil (according to the mechanical resistance) and to obtain approximate location of the sliding surface.

The results of the three surveys are reported in fig. 4. All tests revealed a general increase in soil density with depth. First change is evident at 0.8 – 1 m of depth, probably in correspondence of the soil-subsoil transition. However, at this depth, a still low subsoil resistance is noted; an abrupt change in penetration resistance can be instead observed at about 3-3,5 m of depth, where the bedrock was probably reached.

Since a non-standard penetrometer was used, no relations are attempted of the N-value with specific soil properties, and only qualitative profiles referred to penetration resistance of the soil and subsoil were used, particularly to integrate and validate the results of geophysical tests. The grain-size distribution curve of samples of dismembered material collected within the main landslide body was also obtained, corresponding to weakly silty-clayey sand.

Geophysical Surveys

Two different geophysical methods were applied: respectively, electric and seismic tomography (concerning both P and S waves velocities) along the major and minor axis of the ellipse drawn by the border of the landslide (for location, see fig. 2).

Electric tomographies were acquired with two different spreads of 32 electrodes with 1.5 m electrode spacing deployed along the B-B' and C-C' lines, to provide an image of the slope in both directions. The acquisition used a PASI tomograph and a Wenner- Schlumberger measuring sequence; with such a sequence, it is indeed possible to obtain a good compromise between both vertical and lateral resolution. Due to the relatively shallow expected sliding surface, reduced arrays length were used allowing for an investigation depth of about 10 m. Acquired data were inverted by the commercial inversion code Res2Dinv® (Loke and Barker, 1996).

Seismic tomographies were performed only along the maximum slope line (B-B' line) but, in order to retrieve both S and P wave velocities, different sources and sensors were used. For P waves, an array of 24 vertical 4.5 Hz geophones with 2 m spacing and a vertical hammer source were used; for S waves, an array of 24 swyphones^{tm} (Sambuelli and Deidda, 1999) with 2 m spacing and an appropriate SH source were adopted. Different shot positions were used along the survey line in order to have adequate data for tomographic interpretation. Both arrays were acquired with a Geometrics Geode Seismograph and interpreted for tomography with the commercial code Rayfract®. The use of swyphones^{tm} allowed a reduced time acquisition since no inversion of the source was necessary. The measuring techniques for S wave velocities usually require a more complex acquisition, which are particularly difficult to be attained - especially in complicated logistical conditions such as the ones that commonly characterize landslide sites.

The results of the two electric tomographies are shown in fig. 5. A very shallow (1 – 1,5 m) dry layer overlying a zone of reduced resistivity can be noticed. This zone is located inside the sliding body and is probably related to porous wet material. At the bottom of this high-conductivity zone, evidence of an increase in resistivity can be related to the contact between the landslide body and the bedrock. A very good coherence in the results of the two surveys can be observed, particularly in the overlapping central zone where both images underline a decrease in resistivity in the central part of the slope. This can be explained by the presence of preferential flow path that can have favoured the sliding movement. Indeed, field evidence underlined the presence of a significant amount of water in this area right after landslide activation.

With respect to seismic tomographies, in fig. 6 the results of P and S wave tests are shown. From both images, a clear evidence of the contact between the displaced material and the stable rock can be evidenced, helping to delineate the sliding surface. The P wave tomography seems to identify the presence of a low water table (around 15 m depth for P wave velocities of 1500 m/s). This is coherent with previous data in the area since the tests were executed some times after the rainfall events, and a requilibration of the water level probably occurred. In this respect, the results of the electric tomographies can be reinterpreted by excluding the presence of saturated material near the surface, and by attributing the decrease in resistivity to wet material with some clay content (cf. grain size distribution curves). Due to the increased sensitivity of shear waves to the soil skeleton properties, the S wave tomography is instead more able to delineate the variations in the structure of the soil near the slope. Indeed, the presence of a reduced velocity zone just in the middle of the slope is highlighted. The position of this zone is very coherent with the reduced resistivity of the central portion of the slope body, and can be related to loose material which favoured the water flow in the slope.

Discussion

Very often, small landslides are overlooked in term of geotechnical parameters by scientific research because risk associated with them are usually - but not always – negligible. In particular, small landslides are mostly considered from a statistical point of view, identifying – for example - threshold of rainfall to predict further failures (Aleotti, 2004; Campus et al., 2000; Crosta, 1998). Of course, detailed studies on many small landslide are too expensive in term of cost/benefits, especially if they do not represent a serious risk for society. However, even small phenomena can pose risk to people, lifelines and productive activities.

Instead, if the aim is to understand complex systems (like most landslides), by investigating a small phenomenon may allow to limit the unknowns and point out its peculiarities. In this case, the small size of the studied landslide (both in area and depth) allowed the application of relatively standard methodologies. The integration of these simple tecniques suggests new approaches and solutions which can be applied also to more complex geological situations.

In particular, the applications of multidisciplinary approach allowed to: 1) identify the shape of the sliding surface, 2) characterize the geological materials from a technical point of view and 3) give suggestions about the role of groundwater. Only at this point of the research a numerical modelling, to better understand the triggering of the phenomenon, including the definition of shear strength resistance parameters and pore pressures acting at the time of sliding, is possible.

Field observations and geophysical investigations highlighted that the landslide probably involved also the bedrock, and that the landslide body was composed by silty-sand about 3-4 m thick. Coherently with field observations and dynamic penetrometer tests, the sliding surface extracted from geophysical tests seemed to have a compound shape (rotational and translational). In this respect, in fig. 7 a representation based on the poisson ratio extracted from the P and S wave velocity values is used to relate the results of both seismic and penetrometer tests. A very good correspondence is observed between the two results: particularly, the decrease in poisson ratio from typical values of shallow unconsolidated soils to the ones of more consistent and compacted bedrock is observed with a high correspondence with the increase in penetration resistance. Moreover, a remarkable difference is observed between the different locations of penetrometer tests. In particular, near the PP2 test, a reduced resistance zone was found.

Different conceptual models were supposed in the preliminary stage of the study, and numerical simulations aided to select the most realistic one.

In particular, we were successful to reconstruct the observed sliding surface introducing the following characteristics: 1) a high permeable sandy level below the landslide, were the wet level is located, implemented the simple geology of the slope; this level is probably connected to the channel at the top of the hill thanks to the jointing of the rock mass in that area, 2) a free water table in the Diano d'Alba formation close to the surface ("w" in fig. 8), 3) a pressured fast water circulation in the sandy level ("1" in fig. 8) fed by waters in the channel at the top of the hill.
As a matter of fact, the main triggering mechanisms for this small landslide had both natural and man made origin.
According to field evidence and using this conceptual model, back analysis allowed to obtain a good correspondence in terms of sliding surface.

Conclusions

The multidisciplinary approach used for this small landslide allowed to reconstruct a detailed geological model. Fig. 3 and 8 show the conceptual model of the slope according to geological surveys, which was confirmed by the subsurface investigations. The landslide involved a flysch-type bedrock; it moved - at the top - as a rotational slide, and - in the middle part - as a translational one. The mobilized material turned into a debris flow that swept the road and part of the slope below.

The triggering of the landslide can be attributed mainly to the consistent groundwater incoming along a permeable sandy layer located 3-4 m in depth beneath the landslide. The water incoming was highlighted by surface evidence and confirmed by geophysical surveys which allowed to identify a permeable level just below the wetlands observed at surface. This should have substantially increased pore pressures and made the slope unstable, so that the "engine" of the phenomenon would be under the central part of the landslide body.

At moment, we have no groundwater direct measurements to demonstrate this theory but many evidences agree with our assumption: 1) very wet area at the base of the landslide was still present several days after the slide (notable ground water flow is necessary), 2) the location of this wet area can not be referred to direct rainfall, but is coherent with flows coming along sandstone levels at depth, 3) the recharge area of this permeable level can be placed near divide (probably just on the other slope), through NW-SE open joints and/or faults, and 4) numerical model confirmed this configuration.

The recognition of the influence of the man made channel near the divide as the main predisposing factor for this landslide allowed to design effective countermeasures for the safety of the slope (e.g. hydraulic insulation of the channel boundaries).

In conclusion, this small landslide was a good test site to cross-check data from various sources (geology, geomorphology, topography, geotechnics and geophysics), to collect them in a unique model verified by a numerical simulation that confirmed all the supposed conditions.

Acknowledgments

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Figure

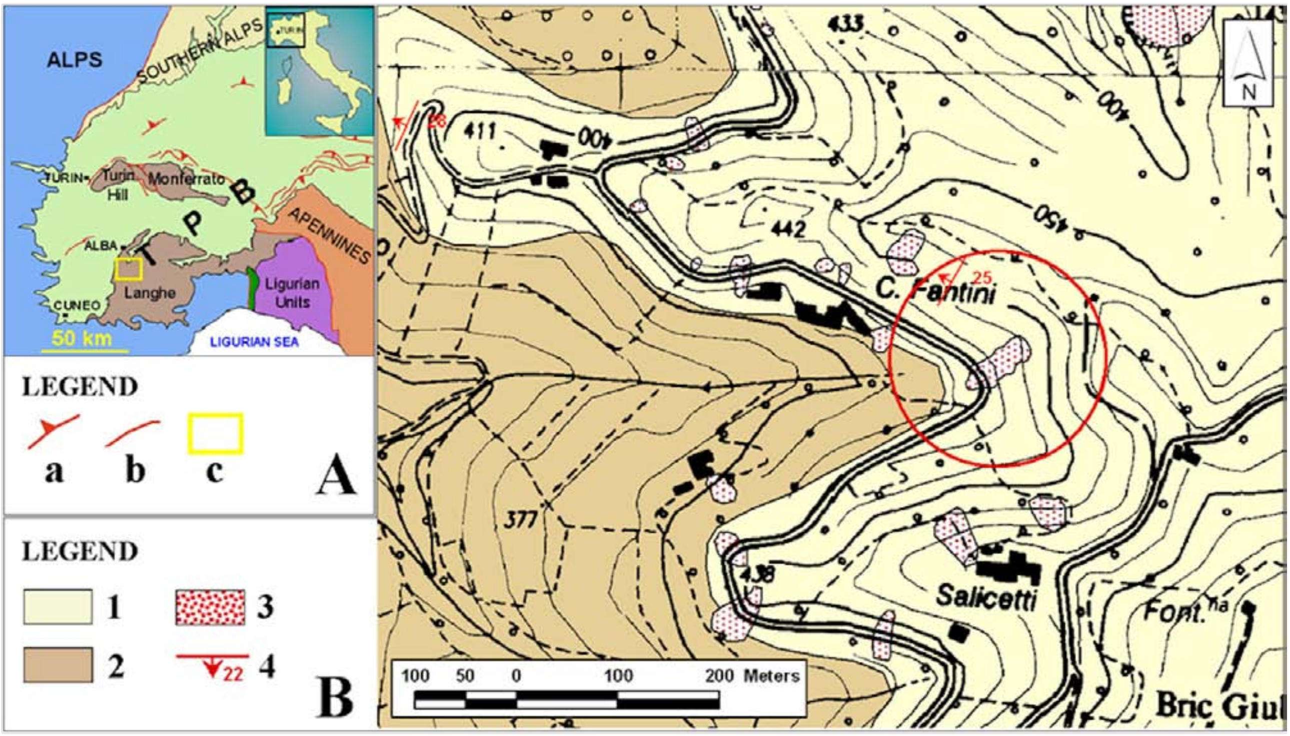


Figure 1

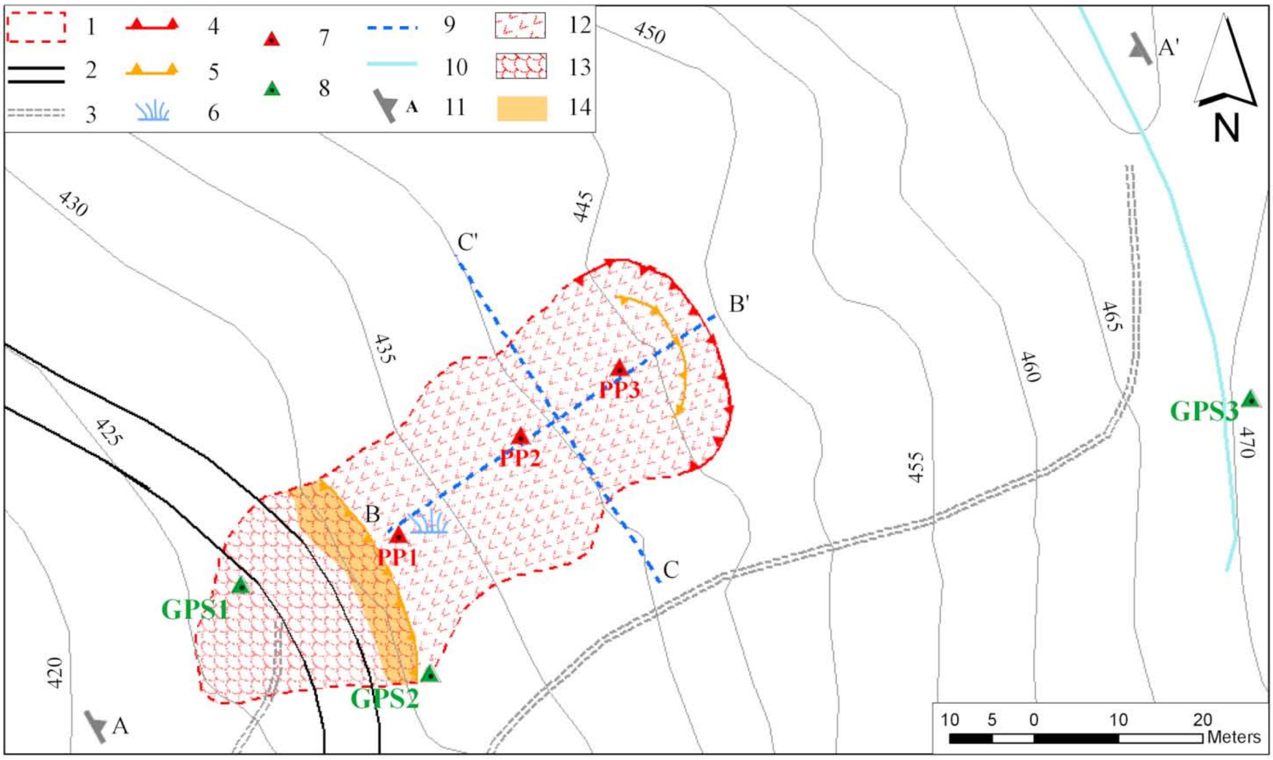
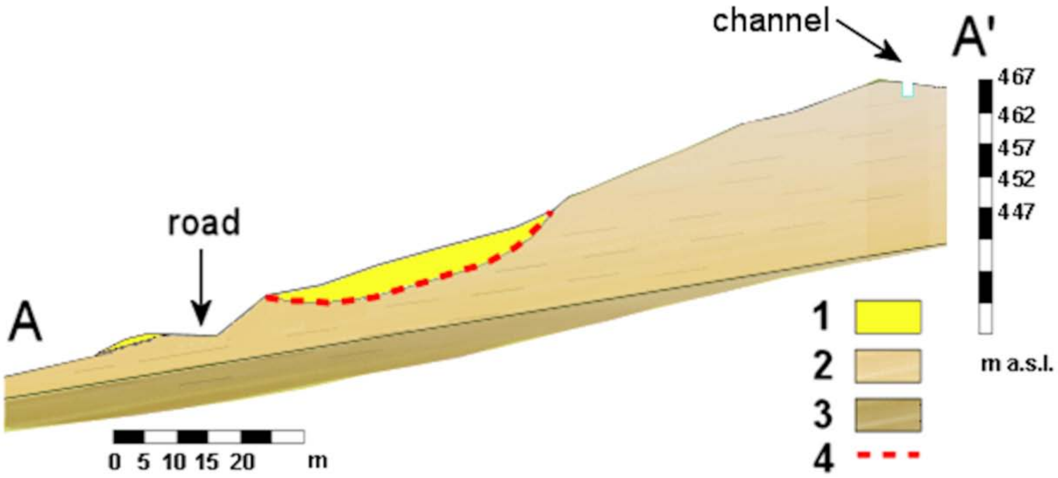


Figure 2



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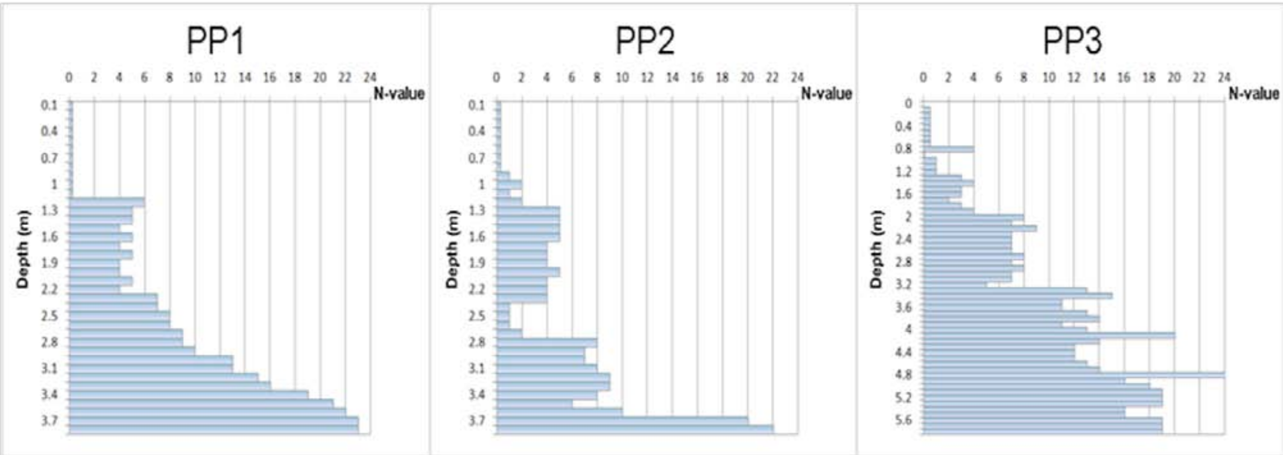


Figure 4

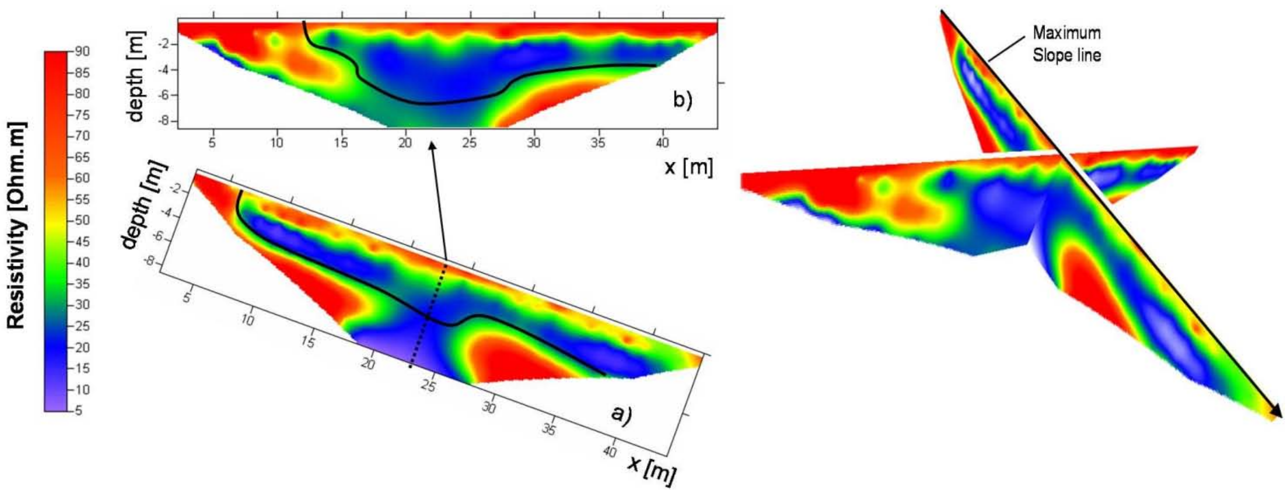
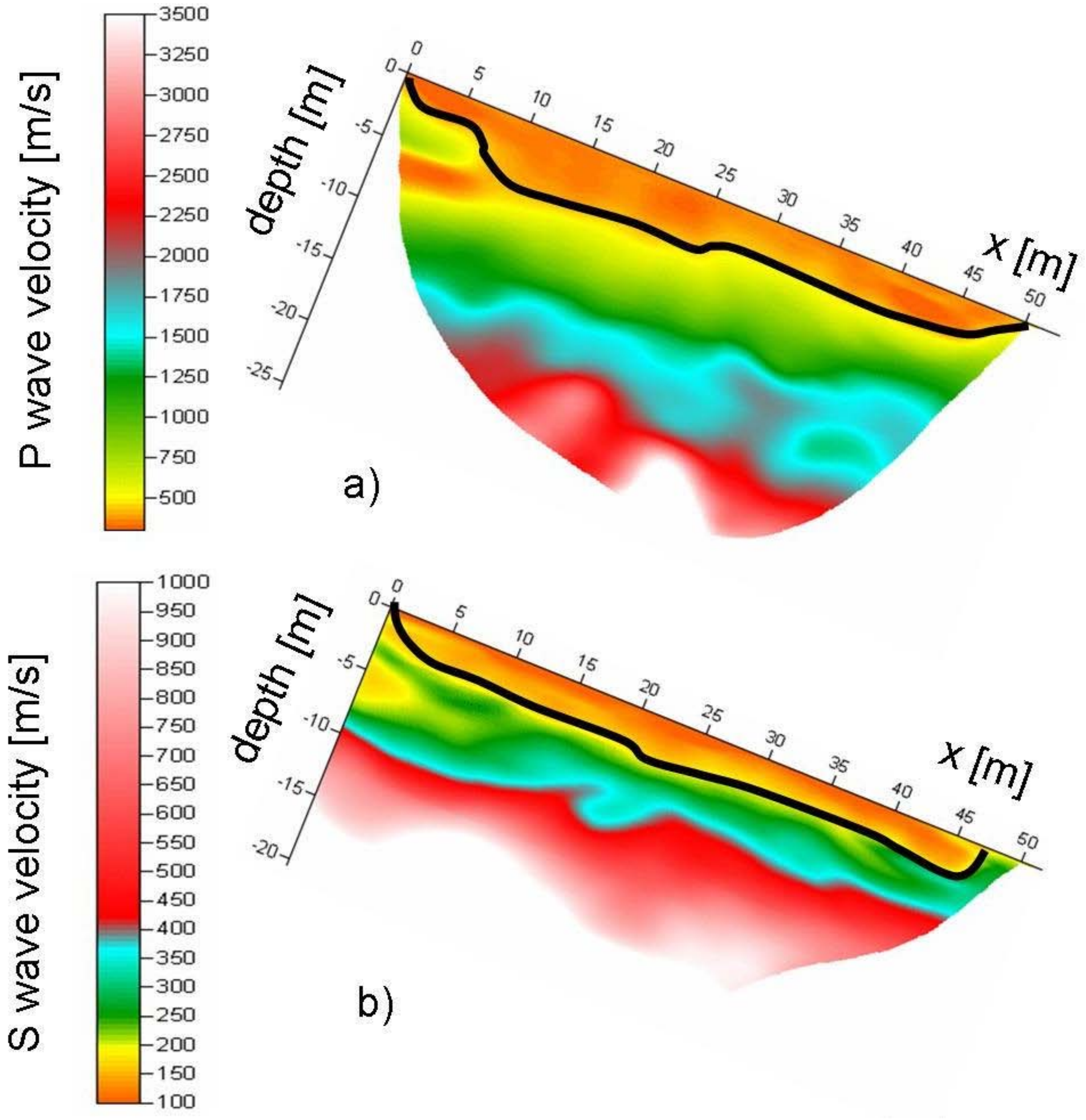


Figure 5


P wave velocity [m/s]
3500
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3000
2750
2500
2250
2000
1750
1500
1250
1000
750
500
depth [m]
x [m]
a)
S wave velocity [m/s]
1000
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Figure 6

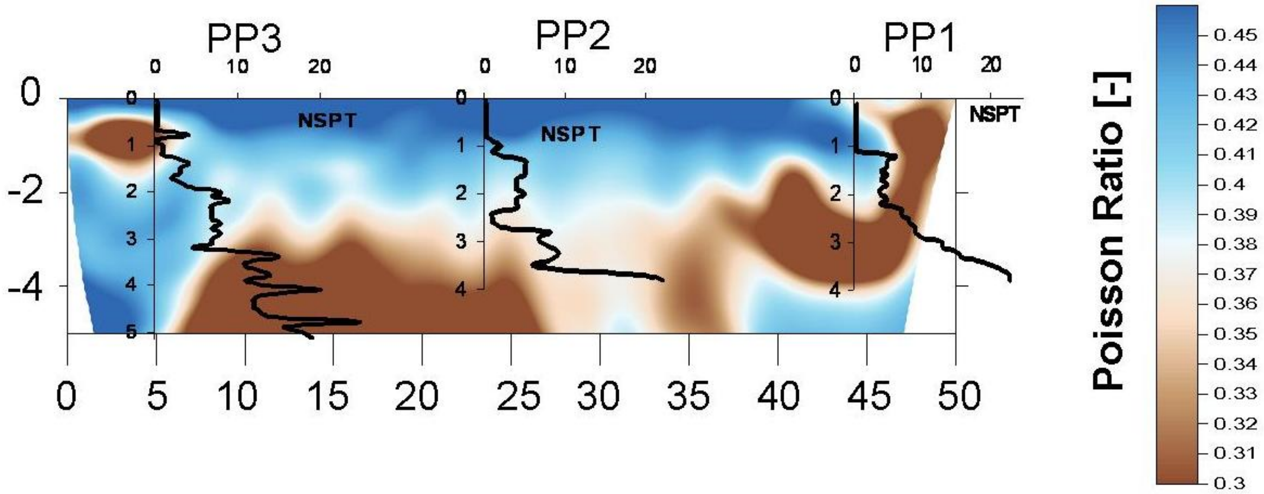

Figure 7

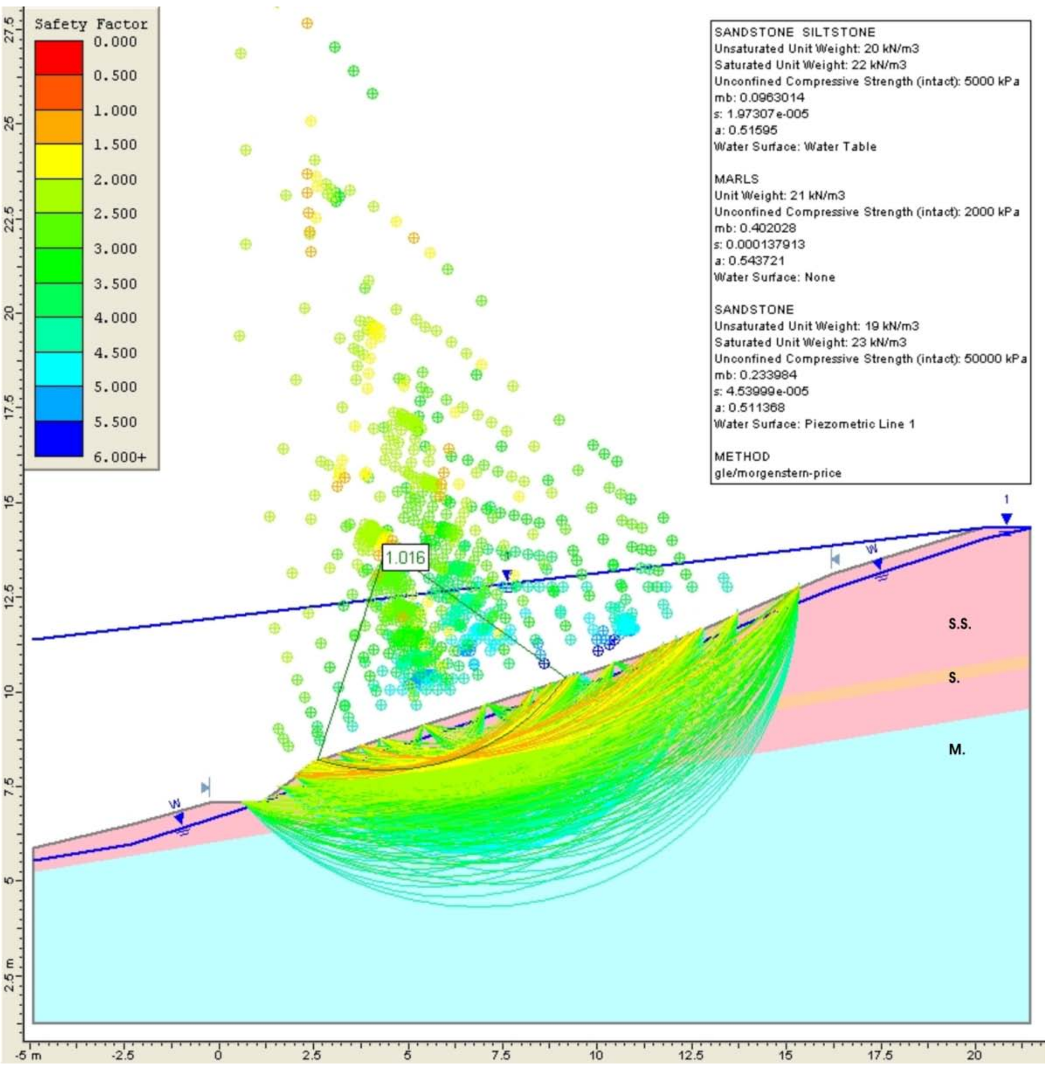

Figure 8

Caption to Figures

Fig.1 - Location map and geological setting of the study area. A) geological sketch map of Tertiary Piedmont Basin (TPB): a - thrust fault, b – fault, c - study area; B) geological setting of the study area: 1 - Diano d'Alba Sandstones F., 2 - Sant'Agata Fossili Marls F., 3 - recent landslides occurred in April 2009, 4 - strike and dip of beds. The studied area is marked by a red circle.

Fig.2: Details of the landslide and of the field investigations: 1 - landslide borders, 2 – road, 3 – track, 4 - main scarp, 5 - minor scarp, 6 – water impoundments, 7 - dynamic penetration test sites, 8 - GPS ground control point and total station bases, 9 - geophysical arrays, 10 - trace of geological section, 11 - slide, 12 - flow, 13 - man-made slope.

Fig.3: Longitudinal section of landslide (for location see Fig 2): 1 - displaced material; 2 - Diano d'Alba Sandstones F.; 3 - Sant'Agata Fossili Marls F.; 4 – sliding surface.

Fig.4 Technical profiles of the dynamic penetrometer tests.

Fig.5 Electric topographies, executed a) longitudinal (B'-B) and b) transversal (C'-C) to the slope, and probable position of the sliding surface (thick black line). On the right, a combined view of the two sections.

Fig.6 - Seismic P wave tomography and seismic S wave tomography executed longitudinal (B'-B) to the slope with probable position of the sliding surface (thick black line).

Fig.7 - Poisson ratio map in relation to of penetrometer tests along the major axis of the landslide.

Fig. 8 – Slope stability analysis with minor safety factor value coherent with measured sliding surface. Keys: S.S. = sandstone and siltstone, S. = sandy level, M. = marl, w = water table in S.S., 1 = pressured water table in S.