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A multidisciplinary approach to landslide modelling: the case of Campodenno, north-eastern Alps, Italy

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ABSTRACT: Campodenno village, laying in the central-western part of the Trentino Region (Northern Italy), is affected by composite landslide phenomena that cause heavy damages to buildings and public facilities. The purpose of the present work was the definition of a complete geological model, to be used to perform stability analyses of sliding slopes. In order to carry out a valid slope stability analysis a complete and reliable geological and geotechnical model of the landslide slope must be performed. All the previous available data, then, have been collected and re-interpreted. The integration of all these data allowed the definition of a preliminary geological and geotechnical model of the slope that, however, resulted to be affected by some uncertainties as regards mainly the spatial distribution of different stratigraphical levels. Because of these uncertainties, some geophysical surveys have been carried out in order to investigate the lateral continuity and hydrogeological properties of the stratigraphic layers and also the thickness of the sliding material. Geoelectrical, seismic and magnetotelluric surveys have been carried on and the interpreted results compared and integrated with the already existing data. In that way, reliable geological models of the Campodenno slopes have been realized to be used for stability analysis purposes.

RIASSUNTO: L'abitato di Campodenno, localizzato nella porzione centro-occidentale della regione Trentino (Italia settentrionale) su di una collina allungata in direzione NW-SE, è caratterizzato dalla presenza di fenomeni di instabilità compositi su entrambi i fianchi della collina, che provocano danni piuttosto importanti a costruzioni ed infrastrutture. La geologia locale è caratterizzata dalla presenza di un bedrock costituito da marne eoceniche fittamente stratificate, al di sopra delle quali si trova una spessa sequenza di depositi quaternari formata da tre livelli con differenti caratteristiche litologiche e, di conseguenza, geotecniche ed idrogeologiche. Le differenti proprietà dei suoli quaternari e la loro distribuzione spaziale danno origine ad una complessa e non completamente chiara struttura dei corpi idrici sotterranei. Lo scopo del presente lavoro è stato la definizione di un modello geologico e geotecnico completo ed affidabile, che potrà essere successivamente utilizzato per l'esecuzione delle analisi di stabilità dei versanti in studio. Tutti i dati disponibili sono stati quindi raccolti, analizzati e reinterpretati. L'integrazione di tali dati ha consentito la definizione di un modello geologico-tecnico preliminare dell'area in esame che, tuttavia, risulta affetto da notevoli incertezze legate principalmente alla distribuzione spaziale dei differenti livelli stratigrafici. A causa di tali incertezze, sono stati realizzati nuovi rilievi mediante metodi geofisici principalmente con il fine di investigare la continuità laterale dei corpi stratigrafici e lo spessore del materiale mobilizzabile dai fenomeni franosi in atto. I risultati dei sondaggi geoelettrici, sismici e magnetotellurici realizzati sono stati, quindi, confrontati ed integrati con i dati già esistenti. In questo modo è stato possibile ricostruire il modello geologico dell'area instabile da poter utilizzare nell'analisi delle condizioni di stabilità e nella scelta degli interventi sistematori.

Key terms: geological modelling, landslide, geophysics methods, hydrogeology
Termini chiave: modello geologico, frane, metodi geofisici, idrogeologia

1. Introduction

The multidisciplinary approach to solve environmental problems connected with landslides is one of the most difficult but it is also the most suitable for planning a correct land use.

The understanding of failure processes involved in landslides may by very hard for reasons arising from the difficulties in evaluating mechanical and hydrogeological behaviour of the involved masses and from the necessity of considering the 3D aspects of sliding phenomena and geological structure of the unstable slopes.

Since global interpretation of the structure of sliding areas is not easy or even impossible, geophysical methods are more and more frequently employed. Reliable 2D and 3D reconstructions of the structure and the identification of different zones associated with particular lithological or hydrogeological characteristics can be obtained. Recent studies have shown, in particular, that resistivity methods have the capacity of identify major details of actual geological and hydrological structures of studied areas (Jongmans et al.,2000; Sumanovac and Weisser,2001; T. Lebourg, et al., 2005). However, this method has been rarely used on landsliding areas mainly because of the morphological setting and the presence of buildings and infrastructures. As a consequence, obtained results need more information from complementary approaches and validation from different methods like seismic reflection and refraction, gravity and magnetic methods.

The purpose of this work was to investigate whether integrated geophysical surveys could provide accurate information on the slipping mass geometry and on the hydrogeological model of the unstable slopes of the village of Campodenno (Trento, Italy), where the evacuation of some buildings revealed to be necessary. Geophysical surveys have been conducted on the unstable slopes of the hill where is located Campodenno (Paoli, 2005). Electrical resistivity, seismic and magnetotelluric survey were carried out to obtain, for the first time on the actual landslides, 3D information on the geological and hydrogeological models and on the slipping surface.

The already existing geological and hydrogeological information on these high risk landslides have been then integrated with the data obtained by different geophysical methods, topographical measures and drillings. The results highlight the importance of multidisciplinary approaches on landslide hazards, combining subjects and disciplines at first sight quite different.

2. Geological and geomorphological setting

The Campodenno village lays in the central-western part of the Trentino Region, on the right side of Non's valley, which presents a N-S extension, on a narrow hill extending NW-SE (Figg. 1, 2). This area is characterized by a wide syncline with a N-S axis coinciding with the valley and a core formed by eocenic well-stratified marls belonging to the "Ponte Pià formation" and the underlying cretacic marly limestones of the Scaglia Rossa formation (Fig. 3). In the western part, the syncline is interrupted by some vertical tectonic structures belonging to the "Trento-Cles Line". This N-S line keeps in contact the cretacic-eocenic terrains with the mesozoic carbonatic units belonging to the Dolomite sequence. This bedrock is covered by thick quaternary deposits, constituted of ancient cemented screes with predominant carbonatic composition at the bottom, to clayey and silty glacial deposits and old debris flows deposits at the top.

The weak properties of both the eocenic marly terrains and the quaternary deposits favour a deep cut hydrographic net, promoting the development of several landslide phenomena.

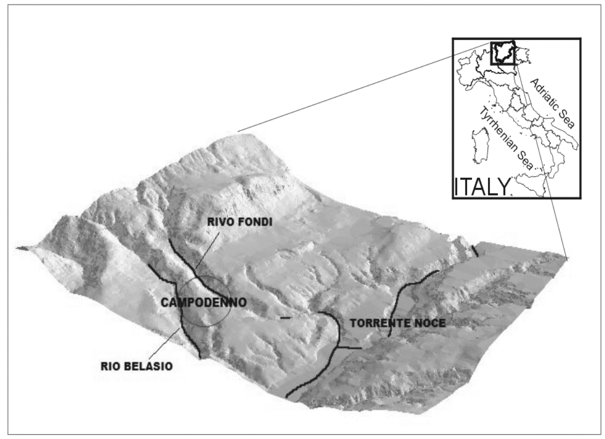

Figure 1 - Location of the study site
Localizzazione dell'area in studio

Figure 2 - Picture of the Campodenno village. In the box, damages on a building
Fotografia dell'abitato di Campodenno. Nel riquadro, Danni presenti su un'abitazione

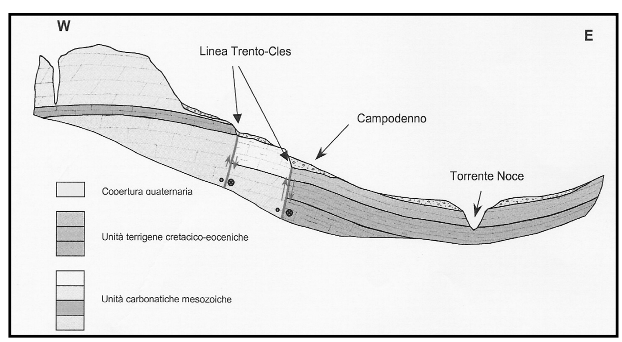

Figure 3 - Schematic geological profile of the study area. 1: carbonatic Mesozoic units; 2: cretacic-eocenic units; 3: quaternary deposits. Scale 1:125.000
Sezione geologica schematica dell'area in studio. 1: unità carbonatiche mesozoiche; 2: unità cretacico-eoceniche; 3: depositi quaternari. Scala 1:125.000

Both sides of the hill of the Campodenno village are involved in compound landslides, having displacement rates from mm/year to cm/year.

3. Field investigations and the geological and hydrogeological models

Since 1999, several ground investigations have been carried out from the Geological Survey of the Trento Province. Nine boreholes have been realized with the aim of reconstruct the stratigraphic sequence of the area (Fig. 4), some of which have been further equipped with inclinometers and piezometers.

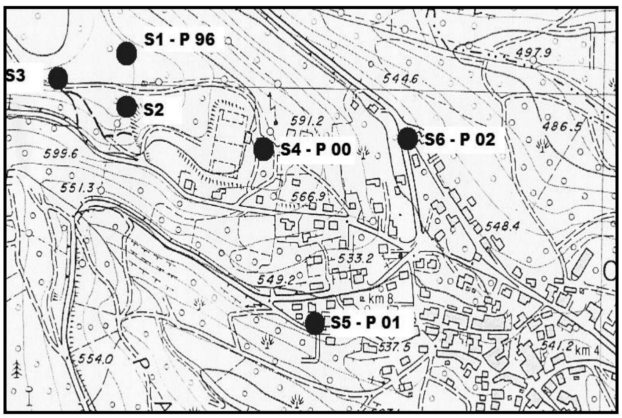

Figure 4 - Borehole location. Scale 1:10.000
Localizzazione dei sondaggi meccanici. Scala 1:10.000

The following lithological sequence in the Campodenno area has been recognized, lying over the marls of the "Ponte Pià formation" (Fig. 5):

– ancient cemented screes with predominant carbonatic composition, highly cemented and fractured in the upslope sector; the thickness varies between 35 m in the W sector, reducing to disappear in the E sector;

– glacial deposits composed mainly by clayey silt with subordinated sans and gravels, having a lenticular shape and maximum thickness of 50 m;

– debris flow deposits, constituted by non-cemented carbonatic gravels with silty and sandy matrix; the thickness varies between 22 m in the central sector to about 4 m in the NW zone.

The hydrogeological model, as results from the geological model and some in situ permeability tests, is constituted by four superimposed continuous levels (Fig. 4): a base level formed by eocenic marls, with very low permeability; a high permeability layer corresponding to the cemented screes; a very low permeability layer formed by pelitic-rich glacial deposits (k=10-9 m/s); a surficial layer of non-cemented debris flow deposits with high permeability (k=10-4 m/s).

The analysis of the hydrogeological sequence and of the piezometric data collected in six boreholes at different depths indicates the presence of two distinct aquifers, the deeper one corresponding to the cemented screes and sustained by the eocenic marls, the surficial one represented by the debris flow deposits and sustained by the glacial deposits. To prove this model, a tracer test was carried out using chemical tracers introduced into some boreholes. The results of these tests do not agree with the assumed hydrogeological model, showing that the two aquifers are not distinct, but connected.

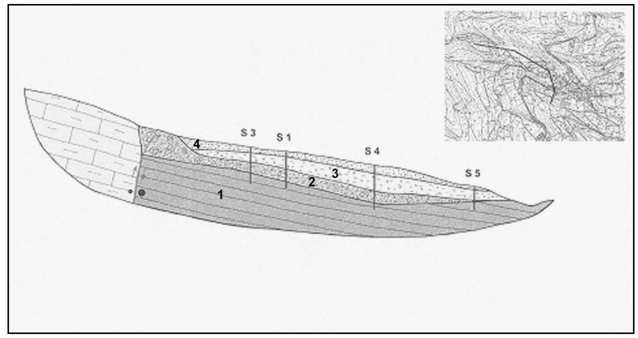

Figure 5 - Stratigraphic and hydrogeological model. 1: Ponte Pià formation; 2: cemented screes ; 3 : glacial deposits ; 4 : debris flow deposits; in 2 and 4 are represented, respectively, the unconfined and artesian aquifers
Modello stratigrafico ed idrogeologico. 1: Formazione di Ponte Pià; 2: conglomerati cementati; 3: depositi glaciali; 4: depositi da debris flow; in 2 e 4 sono rappresentati rispettivamente l'acquifero superficiale e l'acquifero confinato

The landslide kinematics has been evaluated by measuring surface and deep displacements. The displacements, measured using topographic leveling, GPS and satellite SAR interferometry, show two moving sectors located on the two hillsides, separated by the topographically more elevated part of the hill.

Deep displacements have been measured by means of three borehole inclinometers (see figure 6). The results show a different depth of the sliding surfaces of the two slopes. The northward slope presents a sliding surface at about 6 m of depth; the southward area shows the presence of two sliding surfaces, respectively about 7.5 m and 12.5 m of depth. The higher surface corresponds to the top of the glacial deposits.

The displacement rates reach values of 1 cm/year at the surface and along the shallower sliding surfaces, while they are only 0.3 cm/year along the deeper sliding surface (Fig. 7).

4. Geophysical surveys

Because of the uncertainties of the hydrogeological model as after the tracer tests, some geophysical surveys have been pointed out in order to investigate the lateral continuity of the stratigraphic boundaries (Fig. 8). Moreover, these surveys allowed extending to the whole area the information obtained by boreholes, mainly as regards the thickness of the slipping material.

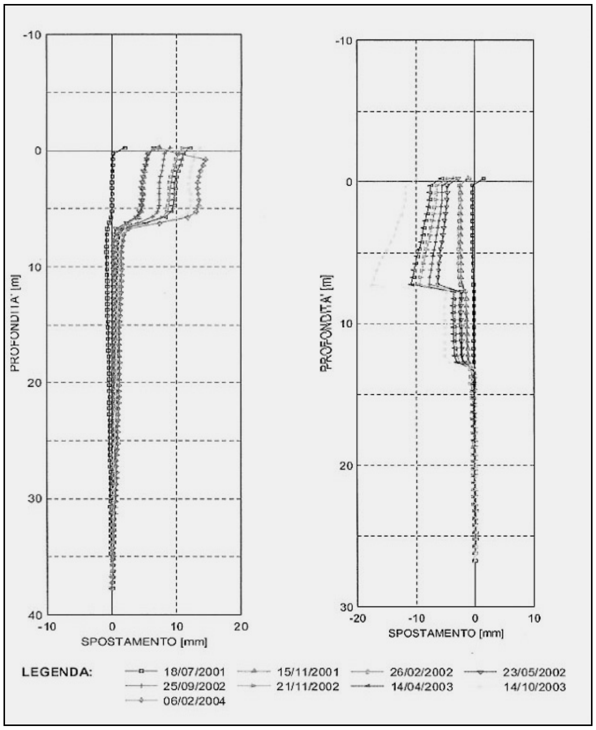

Figure 6 - Inclinometric measures. Left: northward slope; right: southward slope
Misure inclinometriche. Sinistra: versante nord; destra: versante sud

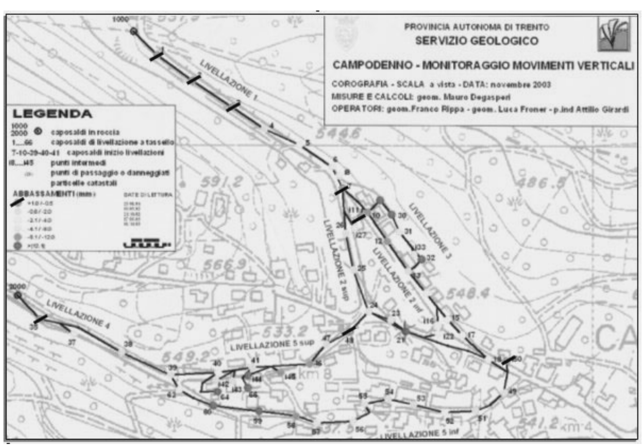

Figure 7 - Displacement map obtained by topographic levelling. Scale 1:10.000
Mappa degli spostamenti ottenuta mediante livellazione topografica. Scala 1:10.000

4.1 Geoelectrical survey

Two geoelectrical survey campaigns have been carried out on the Campodenno hill during 2003-2004. A total of eight resistivity tomographic sections have been realized with a 48 channels system, using an electrodic Wenner-Schlumberger configuration, an electrodic spacing of 5 m and a total length of 200 m. The resistivity sections, reaching a maximum depth of 45 m, show the presence of three different resistivity layers. The surficial layer about 4-5 m thick has resistivity values higher than 50 Ωm, including some local areas characterized by very high resistivity (> 1000 Ωm). The layer below, with resistivity values ranging form 10 to 50 Ωm is broken by two high resistivity sectors, which are continuous from the N two the S, where its dimension is smaller.

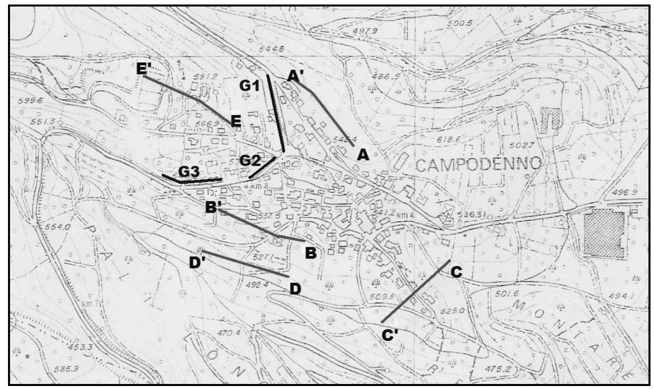

Figure 8 - Geophysical surveys location. Geoelectrical surveys: AA', BB', CC', DD', EE', G1, G2, G3; seismic survey: S; magnetotelluric survey: MT. Scale 1:15.000
Localizzazione dei rilievi geofisici. Sondaggi geoelettrici: AA', BB', CC', DD', EE', G1, G2, G3; sondaggio sismico: S; sondaggio magnetotellurico: MT. Scala 1:15.000

4.2 Seismic survey

In September 2004 a seismic reflection survey has been carried out in the NW sector of the Campodenno village, in order to verify the results of the geoelectrical survey. The surveyed line was composed by 48 geophones spaced 1 m. The results (Fig. 11) show two mains reflectors; the first one, located at 22.5 m of depth, separates the surficial debris flow deposits and the glacial deposits; the second one, at 71.5 m of depth, represents the bottom of the quaternary sequence.

4.3 Magnetotelluric survey

The magnetotelluric method has been used to estimate the thickness of the bedrock formation. One magnetotelluric survey located in SW part of the village show that the Ponte Pià formation has a thickness of about 40 m, as well as the Scaglia Rossa formation below.

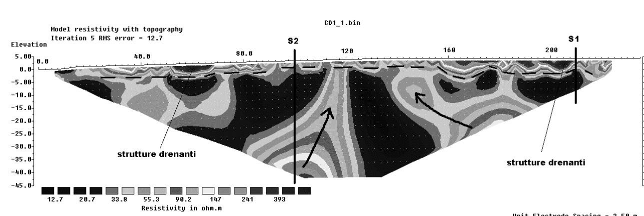

Figure 9. Geoelectrical tomography section A-A'. Section length 240 m.
Sezione tomografica geoelettrica A-A'. Lunghezza della sezione 240 m.

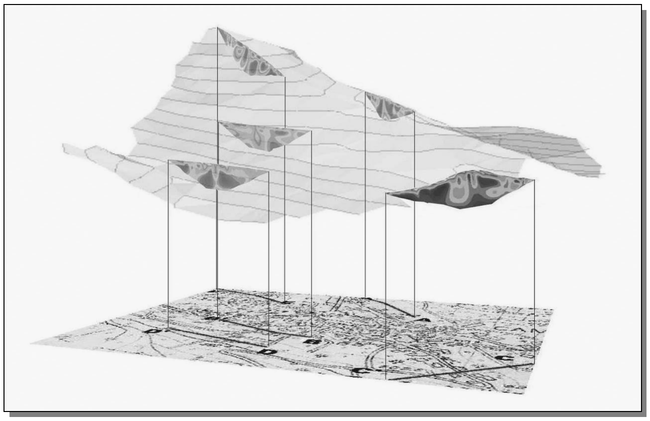

Figure 10 - Geoeletrical profiles overlaid on the Digital Elevation Model of the Campodenno hill; the curved line shows the location of the hydraulically connecting channel between shallow and deep aquifer. Approximate scale 1:25.000

Sezioni geolelettriche sovrapposte al Modello Digitale del Terreno della collina di Campodenno; la linea curva indica la posizione del canale che connette idraulicamente l'acquifero superficiale e quello profondo. Scala 1:25.000

In fig. 12 is shown the results of the MT profile realized along of the Campodenno hills creek.

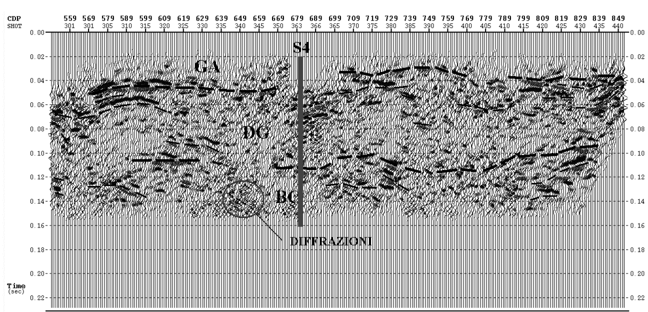

Figure 11 - Seismic reflection section. Section length 140 m

Sezione sismica a riflessione. Lunghezza della sezione 140 m

5. Discussion and conclusions

The geophysical surveys performed on the Campodenno hill showed the peculiarity of the geological model; the hydrogeological structure of the hill changes as regards as that was obtained with the direct surveys.

The geoeletric and seismic surveys allowed to detail with a high precision the quaternary deposits down to the top of the eocenic marls. With the magnetotelluric survey the bedrock thickness has been obtained. The integration of all the information derived by the different surveys allowed to obtain a stratigraphic model more close to the real situation.

The knowledge of the stratigraphic setting of the quaternary deposits allowed to reconstruct a more reliable and accurate hydrogeological model. In fact, the results show that there is one multilayer aquifer, in which the two water levels are separated by a low permeability level corresponding to the glacial deposits. This last level, supposed to be continued in the previous model, is really separated by a more permeable sector, connecting the two aquifers. This sector assumes the form of a channel, transverse to the hill axis and deepening toward NE (Fig. 10).

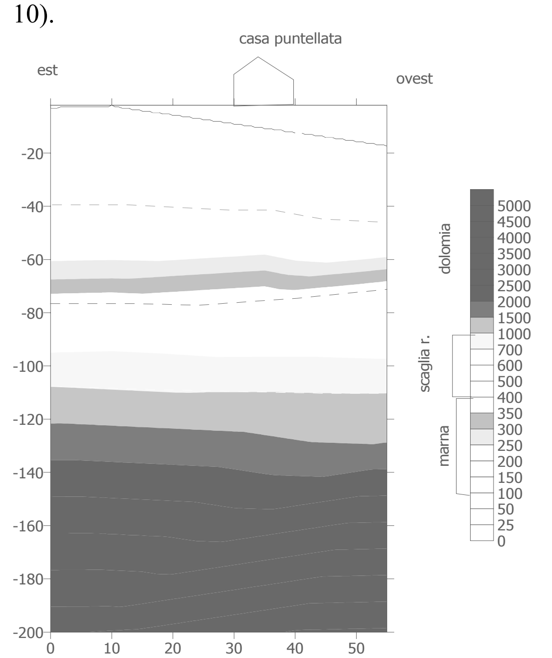

Figure 12 - Magnetotelluric section. 1: Ponte Pià Formation; 2: Scaglia Rossa formation; 3: Dolomia Principale formation. The values are in Ωm. Section length 55 m

Sezione magnetotellurica. 1: Formazione di Ponte Pià; 2: Formazione della Scaglia Rossa; 3: formazione della Dolomia Principale. I valori sono in Ωm. Lunghezza della sezione 55 m

The water flow direction, more or less parallel to the slope uphill, becomes locally almost vertical in correspondence of this permeable sector (Fig. 13); as result, the water level in the upslope area is more shallow than downslope.

The pore water pressure distribution is different from that previously considered: a phreatic condition is shown in the higher aquifer while the deep aquifer is confined, reaching high pore water pressure values in the downslope part.

Some conclusions may be drawn from the analysis and interpretation of all the integrated results:

i) reliable geological models may be obtained only integrating direct mechanical drillings and geophysical surveys;

ii) geoelectric and seismic surveys give accurate results in detecting spatial distribution and characteristics of loose, generally surficial deposits;

iii) different geophysical methods, like the magnetotelluric one, should be used to investigate the deepest and more consolidated levels;

iv) the knowledge of an accurate geological model allows to obtain a reliable hydrogeological model, especially as regards the pore water pressure distribution;

v) finally, all this is the basis of the a correct analysis of the stability conditions, from which proper stabilization works may be designed and realized.

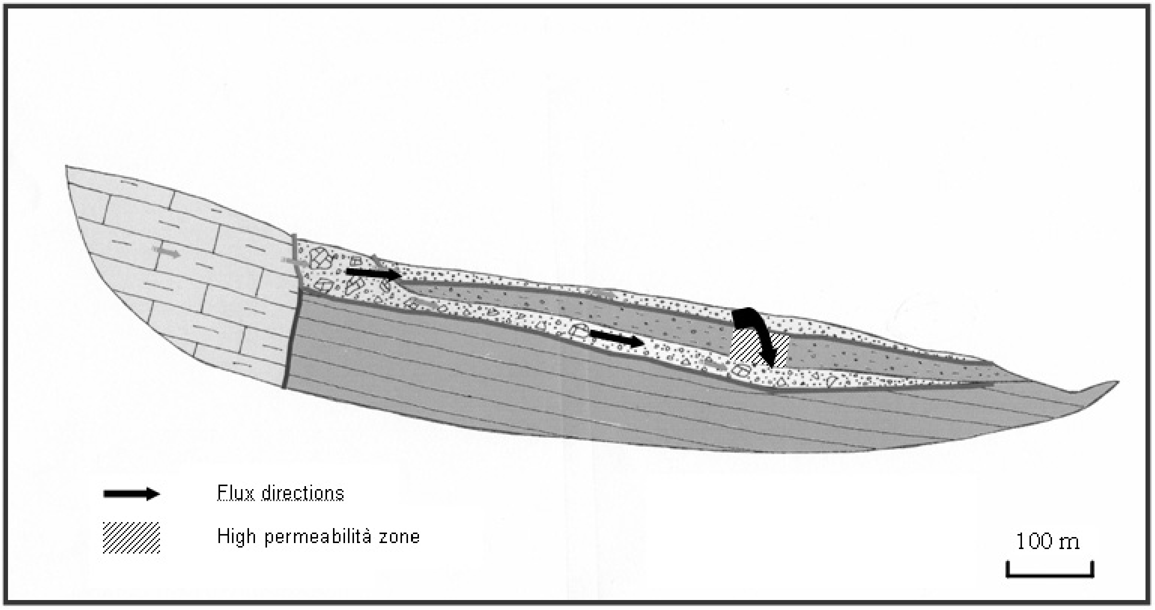

Figure 13 - Final hydrogeological model showing the water flow directions. Dark grey: low permeability levels; light grey: high permeability levels

Modello idrogeologico risultante, con le direzioni di flusso della falda. Livelli a bassa permeabilità in grigio scuro; livelli ad alta permeabilità in grigio chiaro

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