

ATMOSPHERIC AND GEOPHYSICAL MONITORING APPROACH FOR HYDROGEOLOGICAL RISK: A FIRST APPLICATION ON SITE

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ABSTRACT. Climate change in our latitudes increasingly involves the alternation of periods of great drought and extremely localized and intense rainfall events, or the so-called Mediterranean cyclones, which in recent years caused enormous damages and losses both in economic terms and unfortunately in human lives. In order to mitigate these damages and reduce the risks, it is necessary to address the problem in a wide-ranging way. In addition, soil changes resulting from long periods of drought and fires cause a depletion of the soil surface layers which can give rise to the instability phenomena, with heavy rainfalls. A new interdisciplinary methodological approach is presented that can be used on slopes falling in areas of high hydrogeological hazard for the activation of the early warning. The level of susceptibility to instability is determined by evaluating the temporal evolution of the vulnerability of the same slopes due to extreme rainfall events, based on the acquired multiparametric data. The first results of the application of the geoelectrical monitoring at site susceptible to landslides are presented. The geodatabase of the Dipartimento Regionale di Protezione Civile (DRPC) identified 26 sites characterized by high hydrogeological risk in the Messina Province (Italy). Among these, the same area where a dramatic event occurred in autumn 2009 was chosen as a case study.

1. Introduction

Landslide monitoring for the protection of people and risk mitigation has been one of the most important challenges in recent decades. Casagli, Catani, and Del Ventisette 2010 proposed the ground-based SAR interferometry (Synthetic Aperture Radar) as a real time monitoring for slope instability and early warning emergency management support. Such very expensive monitoring is hardly applicable during intense weather events. Bogoslovsky and Ogilvy 1977 demonstrated, for the first time, that geoelectric techniques could be used to interpret landslide structure and hydrological conditions, since the relations between moisture content and electrical resistivity has been determined. Considering that most of the events of slipping the ground are induced by humidity (Gasmu, Rahardjo, and Leong 2000), so the increase in humidity in the subsoil modifies the conditions of interstitial pressure, which influences the shear resistance inside a slope, determining its subsidence (Terzaghi 1936). The geoelectric surveys can be used to deduce the hydrological status of a slope and therefore the shear resistance, which represents a key parameter in estimating

slope stability (Perrone, Lapenna, and Piscitelli 2014; Pazzi, Morelli, and Fanti 2019). In addition, numerous studies have shown that electrical resistivity tomography (ERT) can help to interpret changes in near-surface hydrological conditions (Boyd *et al.* 2021). Hojat *et al.* 2019 showed that the time-lapse ERT can be used to monitor the hydrogeological conditions of landslide bodies in a laboratory test, but it could be also employed for in situ applications, in areas susceptible to shallow landslides.

2. The new multidisciplinary approach

The proposed multidisciplinary methodological approach is aimed at increasing the resilience of territorial systems in relation to the vulnerability of the territory featured by very steep slopes, where the activation of instability phenomena due to extreme rainfall events can be envisaged. It consists of subsystems (Context, Ground and Monitoring data) aimed at the acquisition of data also in real time and their subsequent processing, as well as the management of early warning by the civil protection structures of reference:

- (1) **Context Data:** depending on the location of the territory or an area:
 - 1.1 territorial (landslide susceptibility map and ancillary data, main and secondary roads; levels of functional and systemic vulnerability of the territory),
 - 1.2 social (distribution dynamics of the population in different time slots; levels of social priority associated with elements of the area),
 - 1.3 demographics of greater relevance.
- (2) **Ground Data:** Diagnostic data for the evaluation of susceptibility to damage to the territory
 - 2.1 geometrical and geological characteristics of the area,
 - 2.2 geomorphology and land use,
 - 2.3 geotechnical data.
- (3) **Monitoring Multiparameter Data:**
 - 3.1 precipitation nowcasting related to areas of interest,
 - 3.2 on-site weather station,
 - 3.3 hydrogeological data (level of imbibition of the slope),
 - 3.4 geophysical data (gEOelectric, TDR).
- (4) **Analysis:** numerically assisted simulation based on the acquired data:
 - 4.1 assessment of susceptibility to slope failure,
 - 4.2 possibility of evolution of a given damage scenario towards a paroxysm.
- (5) **Early Warning:** automatic support to decision-makers (Civil Protection)

3. The first experimental approach on site

3.1. Context data. The Province of Messina (Sicily) is an area subject to instability due to various predisposing features: morphology, steep slopes, land use, weak lithologies, etc. Besides it is a high seismic risk zone, seismoinduced landslides can also occur. Numerous events have affected the province, first the most tragic event on October 1, 2009, due to a flood in the Racinazzi and Giampilieri streams on the coast of the Ionian Sea where 37 people died (Ciampalini *et al.* 2015). In addition, between 2009 and 2010, several municipalities were affected by debris flows, complex landslides, and collapses. Even in S. Margherita, the locality where the study was conducted, a flood caused 3 victims on 17

October 1917. It is important to point out that these events were triggered by very localized intense rainfall. The test site is in the hilly village of Santa Margherita, in the southern area of the Messina municipality (Figure 1), where from an essentially agricultural land use in recent decades it is moving to a progressive urbanization. The site was considered of moderate susceptibility, and it was subject to movement of the landslides already registered in the DRPC Database, the first in the past centuries has affected the area with a ridge conformation for an extension of 52,341.93 m². More recently, two portions have been affected by rapid casting movements: the first one northbound for a surface of 441.88 m²; the second one, southbound, for a surface of 732.71 m².

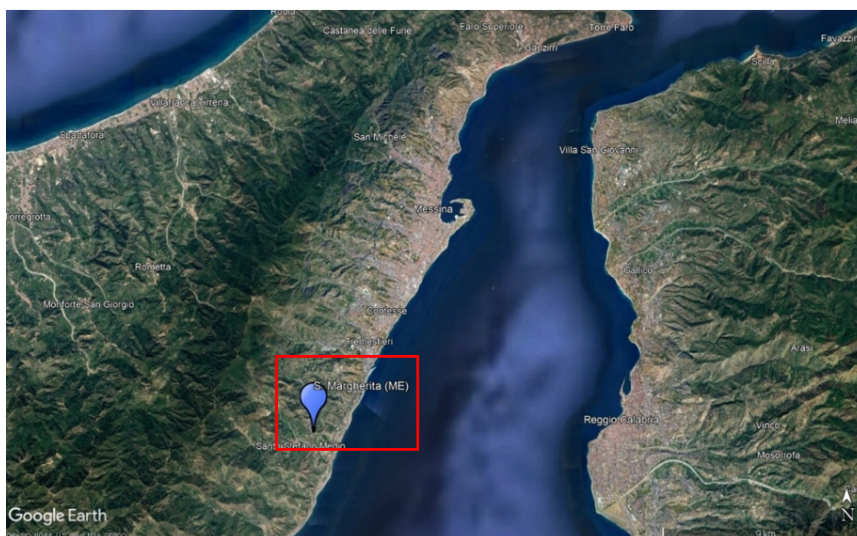


FIGURE 1. Location of the site survey.

3.2. Ground data. The lithology consists of the arenaceous clay facies of molasses. The place is affected by an average acclivity of 52%. The geology of the survey site (Figure 2) is characterized by the presence of two different lithologies: conglomerates and coarse sands (**Mac**) and basal pelitian-sandy alternation and marly clays (**Mm**). The surrounding area is geomorphically complex (Figure 3): the survey site is located to the east close to a zone with a dorsal conformation, which create a part affected by accentuated evident erosion phenomena. The same dorsal on the north side of the hill caused an accumulation of detachment debris. To the west there is the passage of a fault which continues in the north/south direction. To the south, on the other hand, the unchanged morphology continues in the valley, with the presence of the arenaceous clay facies of the molasses (Figure 4).

3.3. Monitoring multiparametric data.

3.3.1. The weather forecast. To improve the Weather forecast, the model configuration was expressly optimized for the complex orography of the Sicilian territory more suitable to forecast this type of intense weather events.

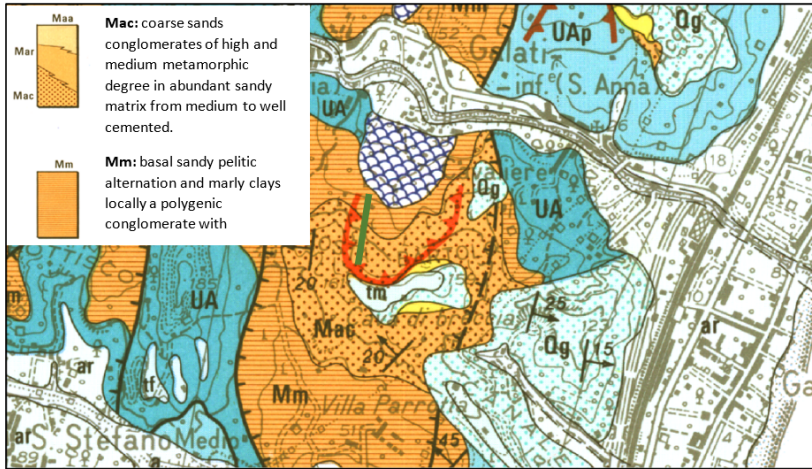


FIGURE 2. Part of the geological map, the thin green stripe indicates the profile line. *Carta geologica di Messina e del settore nord-orientale dei Monti Peloritani (Sicilia NE), scala 1:25.000, Gargano, C., 1994, S.El.Ca., Firenze*

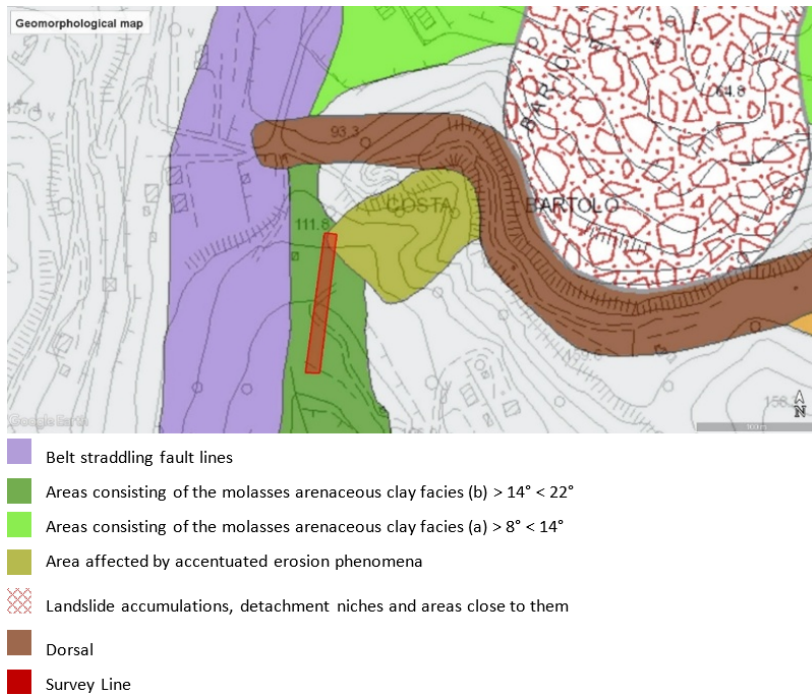


FIGURE 3. Geomorphological map PRG DDR 686 (Natoli), the red stripe indicates the profile line.

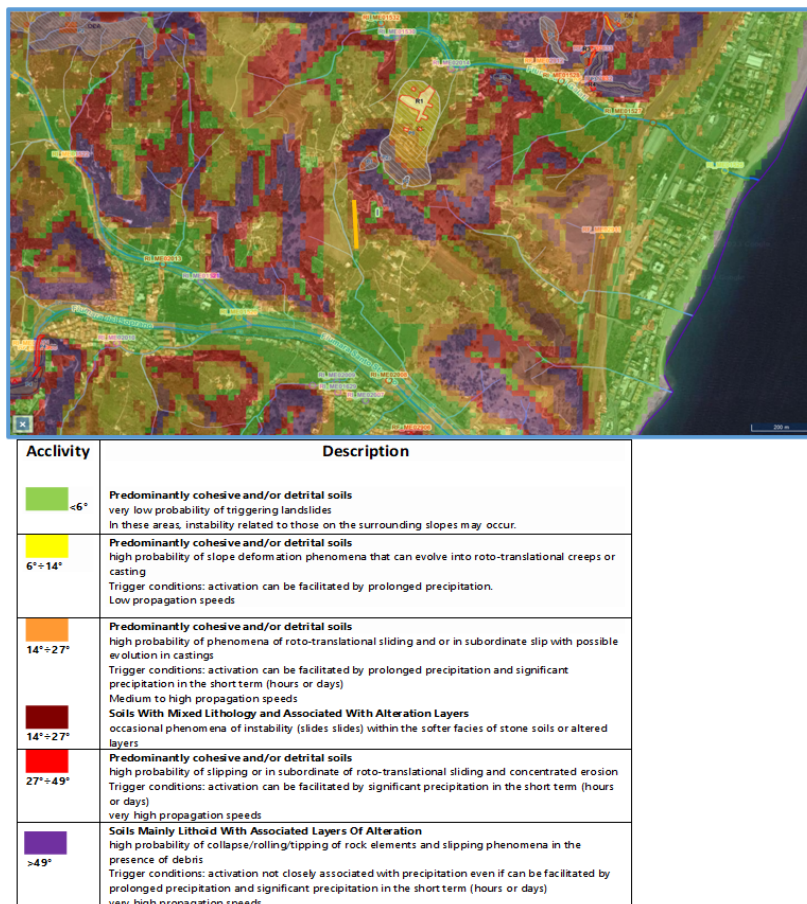


FIGURE 4. Map of the susceptibility to hydrogeological instability CFD IDRO civil protection in the Sicily region and relative legend. The thin orange line shows the survey line position.

Some studies show that forecasts obtained using this kind of model can be very valuable to reduce the hydrogeological impact of extreme events on the ecosystems (Caccamo *et al.* 2016, 2017). It is well known that as far as environmental modelling is concerned, for weather forecasting it is based on a system of differential equations relating to the state of the atmosphere and numerical resolution methods. Furthermore, the boundary conditions require to specify the spatial and temporal scales. These scales, both at the surface and in altitude, are divided and defined in microscale, mesoscale and macroscale. More specifically, the phenomena that are studied in a mesoscale analysis involve a spatial scale between 10 and 1000 km which is further divided into three subcategories:

- Mesoscale α : extends on a horizontal scale between 200-2000 km and is between 2-3 days on a time scale; examples of phenomena of this type are fronts.
- Mesoscale β : extends over a horizontal scale between 20-200 km and develops over a time scale of 1 day; examples of phenomena that can occur on this scale are sea and land breezes.
- Mesoscale γ : extends on a horizontal scale between 2-20 km and spread over a time scale of 1 day; examples of phenomena that can develop in this area are thunderstorms.

Furthermore, this distinction between macroscale and mesoscale allows us to distinguish forecasting models into global scale models Global Model (GM) and local scale models, Limited Area Model (LAM). Global models take into consideration the entire earth's atmosphere, therefore they deal with macro-scale phenomena, while those of a limited area work on smaller portions of territory, defining meso-scale phenomena (Castorina *et al.* 2021). Among the two main global models, used by the most important meteorological forecasting centres, we find the GFS (Global Forecast System) global model elaborated by the NCEP (National Center for Environmental Prediction), the national meteorological center of the United States, and the model produced by European Center ECMWF (European Center for Medium-Range Weather Forecasts). Furthermore, the GMs provide the LAMs with the initial boundary conditions throughout the forecast time. Obviously, it is necessary to interpolate these data with appropriate techniques. While suffering from these uncertainties, LAMs allow to produce very detailed forecasts, valid from one hour to about two days (Castorina *et al.* 2022).

3.3.2. Meteorological data. The rainfall data were collected from the Servizio Informativo Agrometeorologico Siciliano (SIAS) meteorological station of S. Stefano Briga, close to the site, in order to correlate the results obtained from geoelectric surveys to precipitation, analyzing the variations in the geoelectric properties of the subsoil as a function of the water content of the soil. Data refer to the March – October 2022 period (Figure 5).

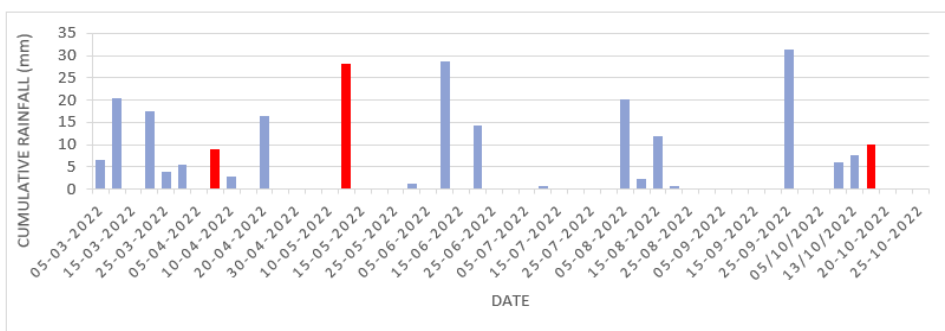


FIGURE 5. Rainfall data from March to October 2022 relating to the rain gauge of S. Stefano Briga (source SIAS).

To consider the effect of the seasonal variation in temperature and the consequent variation in resistivity, the maximum daily temperatures recorded at the Messina station

have been reported (Figure 6). On the days in which the measurements were carried out, there were no significant variations in temperature, $20 \pm 1^\circ\text{C}$, so it can be neglected; therefore, the variation in the geoelectric parameters is mainly due to the water content.

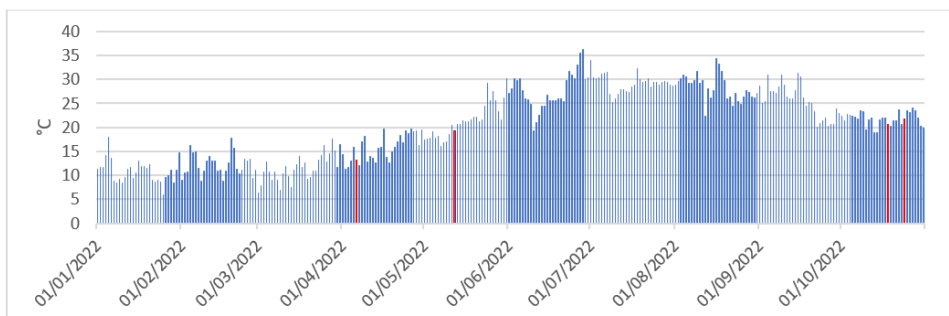


FIGURE 6. High T in the period January-October 2022 relating to the Messina meteorological station (source SIAS).

3.3.3. Geophysical data. 2D and 3D geoelectric acquisitions were carried out at different times of the year, which the results were interpreted in the light of temperature - rainfall data, as shown in the next paragraph.

4. The geoelectrical survey

4.1. Brief theoretical notes. The two geoelectric parameters used in this study that can provide information about the structure and nature of the subsurface are resistivity and loadability. The first is a physical property of matter that represents the spatial resistance to the passage of an electric current in a conductor. It is an extremely variable parameter that depends on numerous factors: permeability, porosity, presence of fluids and their composition and electrical conductivity, ionic content, etc. Therefore, it varies not only from one geological formation to another, but also within the same formation by the degree of cementation. For this reason, the resistivity of rocks and soils cannot be defined by a single value, but by a wide range (tab 1). This dependence is expressed by Archie in a well-known empirical formula (Archie 1942). Loadability is the physical property measured by the induced polarization method. Initially used in mining exploration (Sharma 1997), in recent years there has been an increasing application of this method in different fields, including hydrogeology, the study of the distribution of contaminants in the subsoil, geothermal exploration and hydrocarbon exploration. Only a small range of minerals and soils have significant chargeability values, easily observable when there are minerals in the subsoil that conduct electronically or minerals with a certain clay content. The method is sensitive to the capacitive properties of soils and rocks, which are controlled by the diffusion and polarization mechanism operating at the edge between the mineral grains and the pores of the fluid, or even at the edges of the clay membrane. Therefore, the response is a function of the lithology and conductivity of the fluid.

TABLE 1. Typical range of resistivity and chargeability for the common soils

Rock	Resistivity (ohm.m)	Chargeability [ms]*
Rock With Sulphite	0.01-1	500-3000
Magnetite	0.1-1000	2.2
Sandstones	80-1000	3-12
Shale	10-1000	5-100
Marl	5-100	50-100
Limestones	100-10000	1-5
Dolomite	500-10000	10-20
Volcanic Tuff	1000-107	10-50
Granite	5000-106	10-50
Alluvium	10-1000	1-4
Sands And Gravel	800-10000	3-12
Conglomerate	1000-10000	n.m.
Clay	1-100	3-10
Fresh Water	2-100	0

4.2. Methods. The acquisitions were conducted in an olive grove with the Supersting georesistivimeter equipped with 28 and 56 electrodes, respectively for 2D and 3D survey and 5 m spaced in x and y direction (Figure 7) and dipole-dipole array along the same profile line on different days, as reported in Table2. The Res/IP were measured simultaneously with a measurement time of 2 s. The acquisitions were planned in spring and in autumn, which is usually the wettest season, as unfortunately it has not been in 2022. So, the presented study represents only the first step and is not exhaustive, and the most significant results are 2D tests. The 2D data were then processed with the RES2DINV software (Loke 2012a,b) to obtain Electrical Resistivity (ERT) and Chargeability (ECT) tomography.

TABLE 2. List of the acquisitions the relative dates of acquisition amount of rain and maximum temperature recorded.

Filename	Date	Rain mm in 120h	T (°C)
mixdip	06/04/22	9	13.2
DIP 28	12/05/22	28.2	19.3
DIP 28102	19/10/22	10.1	20.3
DIP2410	24/10/22	0	21.8



FIGURE 7. Photo of the survey line, with the magnification on an electrode planted in the ground.

4.3. Results. For the sake of brevity, only the ERT that showed the most significant variation in rainfall events was reported. The comparison of the ERT (Figure 8) shows that, although the cumulative rainfall difference between May and October is less than 20 mm (Figure 5), the resistivity values in May are much lower than those in October. Figure 8A illustrates the ERT related to the wettest period, highlighting two low-resistivity anomalies, approximately 5 Ω -m, presumably due to the higher water and clay content. At 70 m, two high-resistivity zones, around 300 Ω -m, can be observed: the superficial one is attributed to the concrete road, while the deeper anomaly, at 20 m, could be due to sandstone and conglomerates. Finally, in the lower part of the profile, the presence of two marl layers with different water contents could explain the observed resistivity variation. Figure 8B shows that in the surface layer, approximately 5 m thick, the influence of trees and their root systems is significant, as they retain water and generate bioelectric potentials that contribute to decreasing resistivity and increasing chargeability. All the elements identified in Figure 8A have higher resistivity values in Figure 8B.

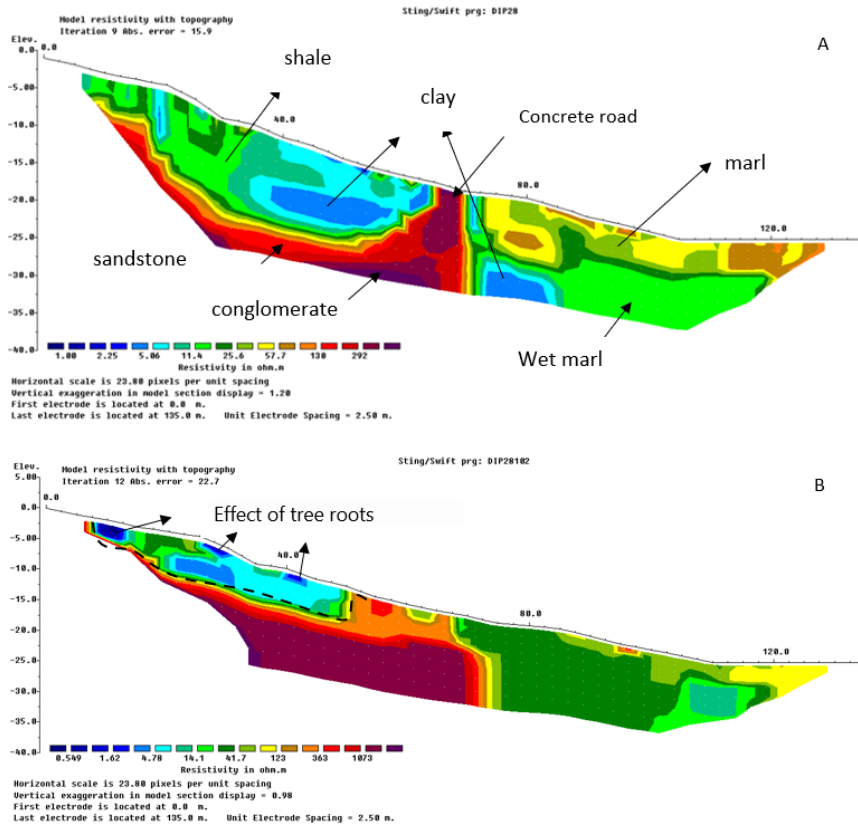


FIGURE 8. Electrical Resistivity Tomography (ERT): Results of the inversion survey of the 12/5 (A), and of the 19/10 (B).

The two ECT, beyond the aforementioned bioelectric potentials of the surface layer, highlight the alternation of marls, shale and layered clay lenses, a few meters thick. Depending also on the water content that causes strong variations in chargeability and anomalous areas with high chargeability, the soil characterization is impractical with ECT data alone. Another critical issue is that generally, the measured chargeability values cannot be compared with precision since the tables in the literature may have different integration times. The interpretation highlighted in Figure 9 was obtained by joint interpretation with ERT to be more consistent (De Domenico *et al.* 2006). The lack of literature data referring to the chargeability value of conglomerates (n.m. in tab2) makes the interpretation of the anomalous zone at the bottom of the ECT problematic Figure 9B.

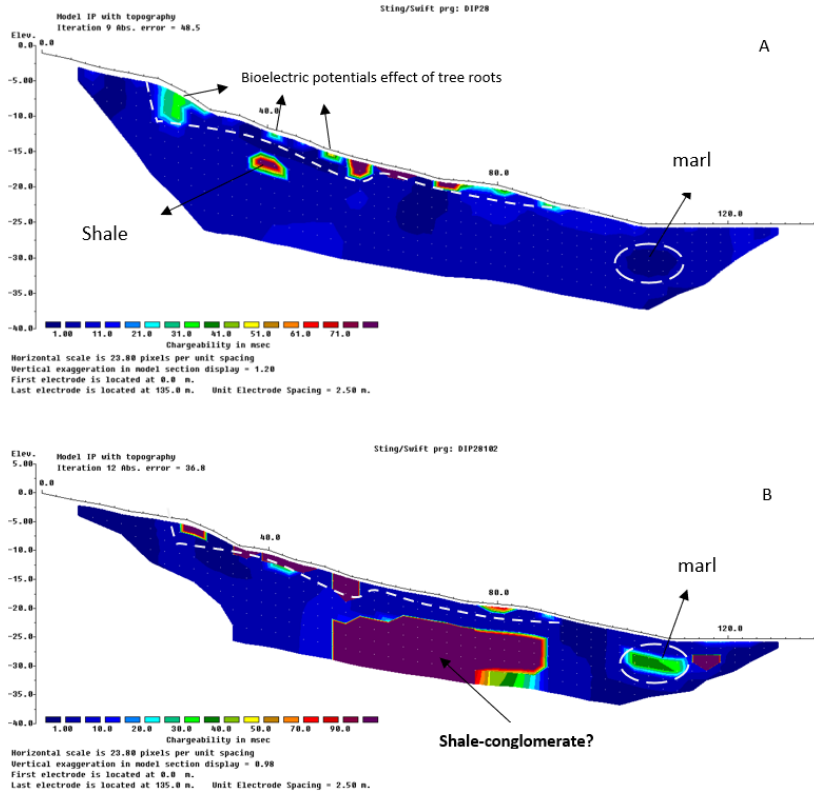


FIGURE 9. Electrical Chargeability Tomography (ECT): Results of the inversion survey of the 12/5 (A), and of the 19/10 (B).

5. Conclusion

This study represents only a first approach with the aim of highlighting the hydrogeological risk mitigation strategy in view of future calamitous events. The proposed application, even if initial and partial, of the whole approach shows that the joint use of geological and geomorphological studies and rainfall and geoelectric parameter monitoring of the territory can lead to the determination of the sliding area with its possible triggering processes. The amount of rain recorded during the period of the surveys was not such as to allow the realization of an in-depth study over time with the study of time lapses, the determination of the water percentage in the soil. The presence of clays that involve an impermeable horizon makes the problem even more critical, as in this case, where the study of chargeability can give a valid support. To improve the modelling and carry out simulation studies regarding the landslide scenario, further detailed studies are needed for a complete hydrogeological characterization of the soil piezometers or TDR could be used to evaluate the water content and determine the geotechnical characteristics through drilling or laboratory tests. The use

of different arrays that reach a greater depth can provide more information on the subsoil, possibly extending the monitoring period to record greater amounts of rain. Automation with wireless instruments, already commercialized, the synchronization of the time interval within which to make measurements and the forecast system.

The proposed approach is flexible and can be expanded or restricted according to the risk factors and exposure of the individual territories, especially in the first phase, the CONTEXT DATA. In this case, the context was chosen to be quite simple to test above all the validity of the central steps, GROUND and MONITORING DATA, which are the most expensive and innovative, especially geoelectric monitoring, which is absolutely absent in the already detailed database of the regional civil protection, being a valid support for the determination of the alert level.

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