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Research Article

A Prototype System for Time-Lapse Electrical Resistivity Tomographies

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A prototype system for time-lapse acquisition of 2D electrical resistivity tomography (ERT) and time domain reflectometry (TDR) measurements was installed in a test site affected by a landslide in Basilicata region (southern Italy). The aim of the system is to monitor in real-time the rainwater infiltration into the soil and obtain information about the variation of the water content in the first layers of the subsoil and the possible influence of this variation on landslide activity. A rain gauge placed in the test site gives information on the rainfall intensity and frequency and suggests the acquisition time interval. The installed system and the preliminary results are presented in this paper.

1. Introduction

Landslides are complex geological phenomena depending on many factors. In order to study these factors, to understand the triggering mechanisms of the movement, and to monitor its dynamic evolution it is necessary to apply a multidisciplinary approach. The rainwater infiltration into the soil and the increase of pore water pressure in the vadose zone can be considered one of the main causes of shallow landslides triggering. Usually, the standard techniques used to measure the water content of the soil and the water table levels in areas of potential instability are the TDR method and the piezometric measurements, respectively. These techniques, while allowing to obtain direct information of the considered parameter, provide only 1D information. Considering that landslides are volumetric phenomena it is a clear need to experiment new investigation techniques which can provide at least 2D hydrological information. It would be better if this information could be continuous in time.

Recently, the literature reports many examples of application of indirect (geophysical) methods for the study and the estimate of water content in the first layers of the subsoil. Among these, the electrical resistivity tomography (ERT), usually applied to obtain information about the geometrical features of the landslides and estimate the thickness of the slide material [1–8], has been tested to obtain information on the temporal and spatial patterns of water infiltration processes [9–15].

The aim of this work is to present a prototype system planned to obtain time-lapse 2D ERT and TDR measurements in a landslide area located in Basilicata region (southern Italy). The system was planned with the aim to estimate the variation of electrical resistivity and soil moisture values in a long period and to obtain information about the influence of precipitations and seasonal changes on them. Very preliminary results allowed us to verify the functioning and confidence of the system, to decide the acquisition time interval, and to obtain information on the yearly variation of resistivity values.

The system was developed in the frame of MORFEO (Monitoraggio e Rischio da Frana mediante dati EO) project funded by the Italian Agency Space (ASI) and finalized to the activities of the Italian Civil Protection Department (DPC) in the landslide risk management.

2. Test Site Description

The planned monitoring system was installed in a landslide area located in Picerno territory at the western side of

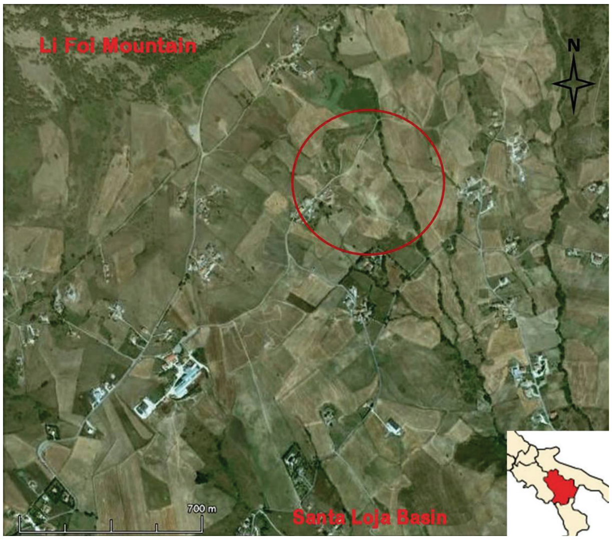

FIGURE 1: Study area location (from Google Earth, modified).

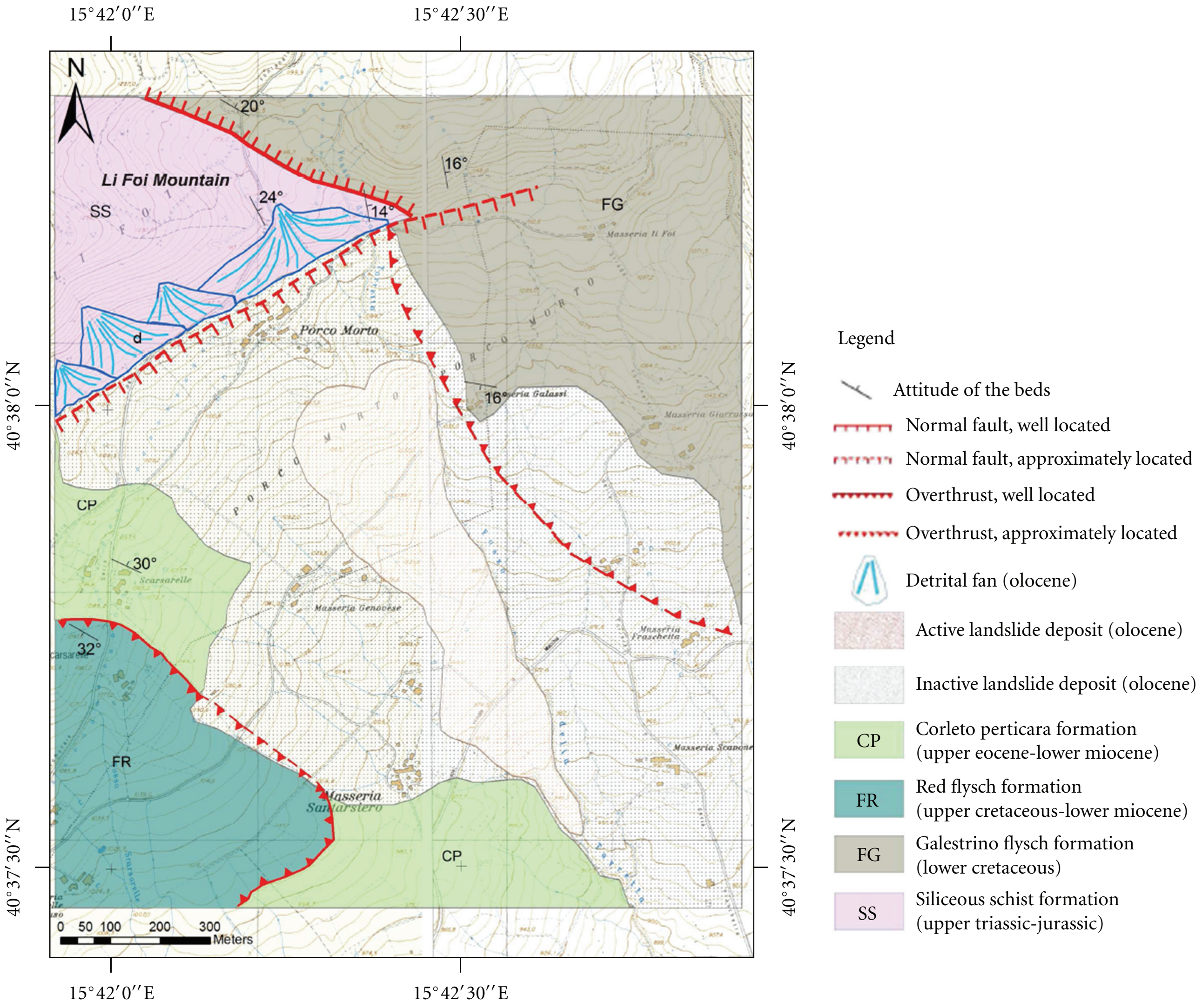

FIGURE 2: Geologic map of the area (from [1]).

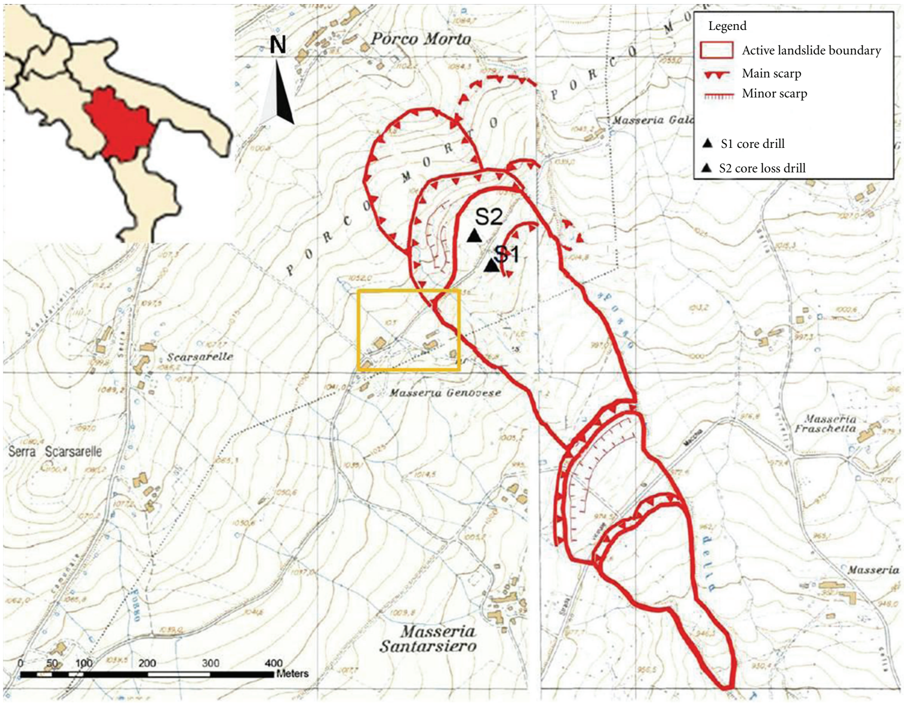

Figure 3: Geomorphologic map of the landslide (from [1] modified), yellow square includes the area where the system was installed.

Figure 4: Location of the acquisition profile (from Google Earth, modified).

Basilicata region (southern Italy), within the Apennine chain (Figure 1). The area has been frequently involved in reactivation phenomena, the most recent ones occurred on March 2006 after continuous and intense snowfalls.

Terrains affected by landslidesbelong to the Pignola, Abriola facies of the Lagonegro Unit. In particular, there are four main lithological formations outcropping on the slope that in order of sedimentation [16, 17] are (Figure 2):

(i) Siliceous Schist (upper triassic-jurassic), outcropping along the slope of Mount LiFoi;

(ii) Flysch Galestrino (lower cretaceous);

(iii) Flysch Rosso (upper cretaceous-lower miocene);

(iv) Corleto Perticara Formation (upper eocene-lower miocene).

The most recent terrains are characterized by the debris outcropping at the toe of Mount LiFoi.

The Siliceous Schist formation has a thick of 240 meters and is constituted by red and greenish shales with a typical rupture cleavage called "pencil cleavage." In addition, there are red and green jaspers embedded with layers of radiolarites and flint. Lastly, manganese jaspers until they reach the Galestri formation.

The Flysch Galestrino formation is less thick than the Shist formation (about 200 m) and consists of alternating black claystones and siliceous marls, calcilutites and marly limestones, marls, and leaf clay.

The Flysch Rosso formation made of jasper, siliceous claystones, calcarenites, red and green marls is in eteropic succession with Argille Varicolori and Corleto Perticara formations [18].


(a) (b)

Figure 5: Syscal Pro- and Mini-Trase equipment connect to the pc (a) and the 48-channel ERT monitoring system (b).

All lithological formations outcropping along the slope are in tectonic contact with each other. Therefore, the Siliceous Schist formation is in tectonic contact with the Flysch Galestrino and Corleto Perticara formations through normal faults which lowered the young ones in respect to the ancient.

The top of the slope in the study area is characterized by recent sedimentary debris due to a certain number of mass movements occurred in the last sixty years.

The landslide classified as a complex retrogressive roto-translational slide is 600 m long and 230 m wide with an altimetry range varying between 1072 m a.s.l., at the main crown, and 978 m a.s.l. at the toe (Figure 3).

The profile of measurement, placed in the upper part of the landslide close to its right lateral boundary, is 47 m long (Figure 4).

The investigation depth reached is about 8 m according to the hydrological characteristics of the area in which the maximum piezometric level is measured at 2 m from ground level.

3. Prototype System and Acquisition Procedure

The prototype system is composed of different units and was planned with the aim to monitor in real-time the electrical resistivity and soil moisture patterns in the first layer of the subsoil.

The two fundamental units of the system are the *geoelectrical monitoring system* and the *TDR system*.

The geoelectrical monitoring system consists of 48 steel electrodes and a 48-channel cable connected to a resistivimeter Syscal Pro Switch 48 of the IRIS Instruments; the electrodes are buried in the soil at 0.5 meters depth, at the distance of 1 meter. The resistivimeter is linked to a pc used to store data and to manage the time when the acquisition starts, and the time interval between two consequential ones (Figure 5). The software used to control time-lapse acquisitions is Comsys Pro of the IRIS Instruments, operating by a script.

The TDR system is composed by 4 probes 20 cm length, buried at two different depths (1 m and 1.5 m) along the same profile of the geoelectric monitoring system. Two probes in correspondence of the 14th electrode and the other two in correspondence of 35th. All probes are connected to the Soil Moisture Equipment Corporation TRASE, which acquires and stores data. Also TDR system is connected to pc to be managed in remote control.

A weather station was installed in the area very close to the profile and linked to the pc. The station consists of a rain gauge to quantify the amount of rain falling in the area, a sensor to measure the air temperature and another one to determine speed and direction of the wind (Figure 6).

The electric current supply for the whole monitoring system is guaranteed by an uninterruptible power supply (U. P. S.).

The system was planned to be controlled in remote by an operator, who can decide day by day how to change acquisition parameters. After each acquisition the system sends an e-mail with attached the data file acquired to three different technicians involved in the check of the correct working of the system.

From September 2009 to January 2010, some ERTs were performed every week to test the system and its setting. For the acquisition three different electrode configuration were used: Wenner, Wenner-Schlumberger, and Dipole-Dipole, in order to choose the configuration that better emphasizes the features of the subsoil and the presence of the piezometric surface. At last, considering the better resolution of horizontal structures and the low noise recorded (better signal response), Wenner array was chosen. The system started to acquire and store data using "time-lapse" mode on 2 February 2010. At first, the number of acquisitions was fixed in four per day starting from 1.30 am (GMT + 1), with a time interval of 6 hours between two consecutive ones. This condition has lasted five months, till the end of June 2010. Then, the number of acquisitions was fixed in two per day, so

Figure 6: The weather station installed in the site.

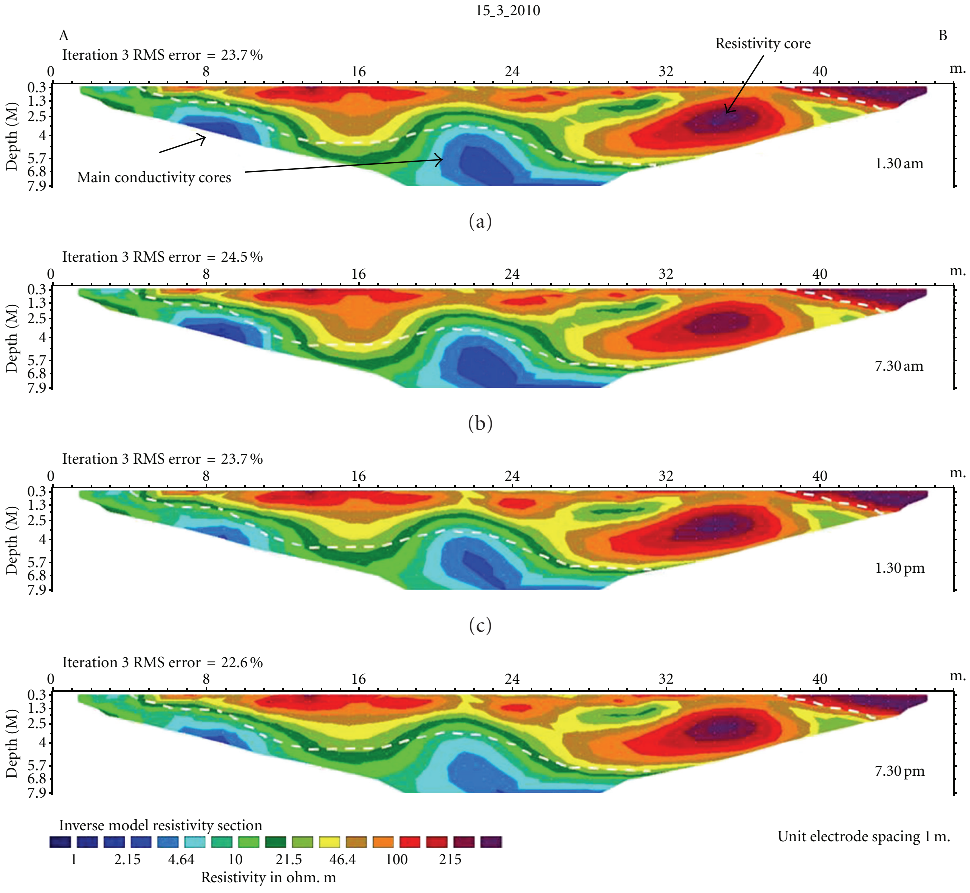

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Figure 7: ERT related to the 15/03/2010 daily cycle of acquisition.

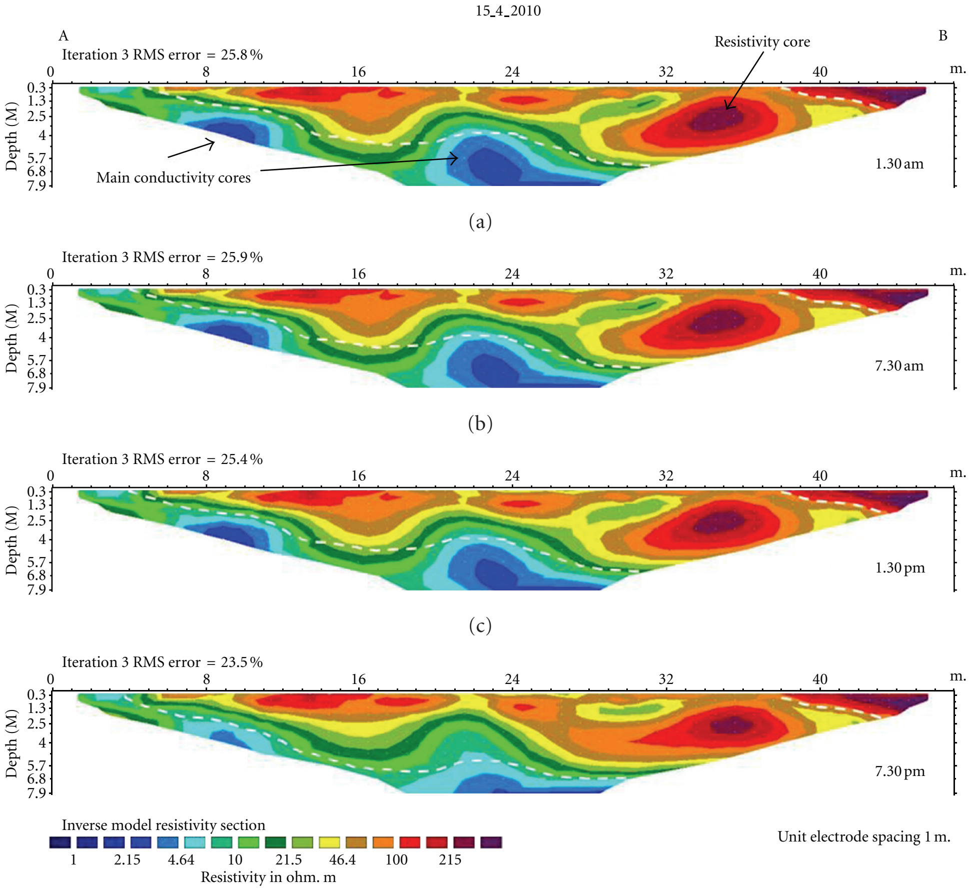

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Figure 8: ERT related to the 15/04/2010 daily cycle of acquisition.

from 1th of July 2010 until now, system is acquiring with an interval of 12 hours, starting from 5 am (GMT + 1).

TDR acquisitions program is similar to the geoelectric one; it started with four acquisition per day, with a shift of one hour from the geoelectric survey. Then, from 1st of July 2010 it is acquiring soil moisture data at the same hour of geoelectric data, two times per day. Also for TDR survey it was decided to acquire with an interval of 12 hours, starting from 5 am (GMT + 1).

Weather station, instead, started to store data just from 2nd of February 2011, with interval of two hours. The number of acquisitions is 12 per day, so the amount of precipitations is extremely detailed. For the preliminary analysis we used the rainfall data acquired by another station located 3 kilometers far from the area of investigation.

4. Preliminary Results

The results reported in this paper concern the first acquisition period from February 2010 to June 2010.

In the first five months, from the 2nd of February to the 30th of June, time-lapse tomographies were performed every days with a frequency of four acquisition per day. Exactly, the cycle of acquisition started 1.30 am (GMT+1) and ended at 7.30 pm (GMT+1), with a time interval of 6 hours between two consecutive ones.

At the first, the system has been tested to verify its correct working. During February 2010 it was necessary to verify the correct functioning of the monitoring system in time-lapse mode and its stability in time. Hence, the main analysis of the resistivity data started from March 2010.

A preliminary analysis of the data has shown a considerable stability of the system and its correct working. No significant variations of the resistivity values were observed during a daily cycle of acquisition. This is also highlighted by the ERTs reported in Figures 7–10 showing the resistivity distribution in the subsoil of four daily cycles; more precisely acquisitions are referred to the 15th of March (Figure 7), the 15th of April (Figure 8), the 15th of May (Figure 9), and the 14th of June (Figure 10). Time interval between each acquisition is one month. The apparent resistivity data were inverted by using the RES2DINV software that uses an algorithm based on the smoothness constrained least square inversion implemented by using a quasi-Newton optimization technique, suggested by Loke and Barker [19].

All ERTs are characterized by the same distribution of resistivity and show a large range of values ($2 < \rho < 300\ \Omega$m), picked out by the presence of two main zones with different

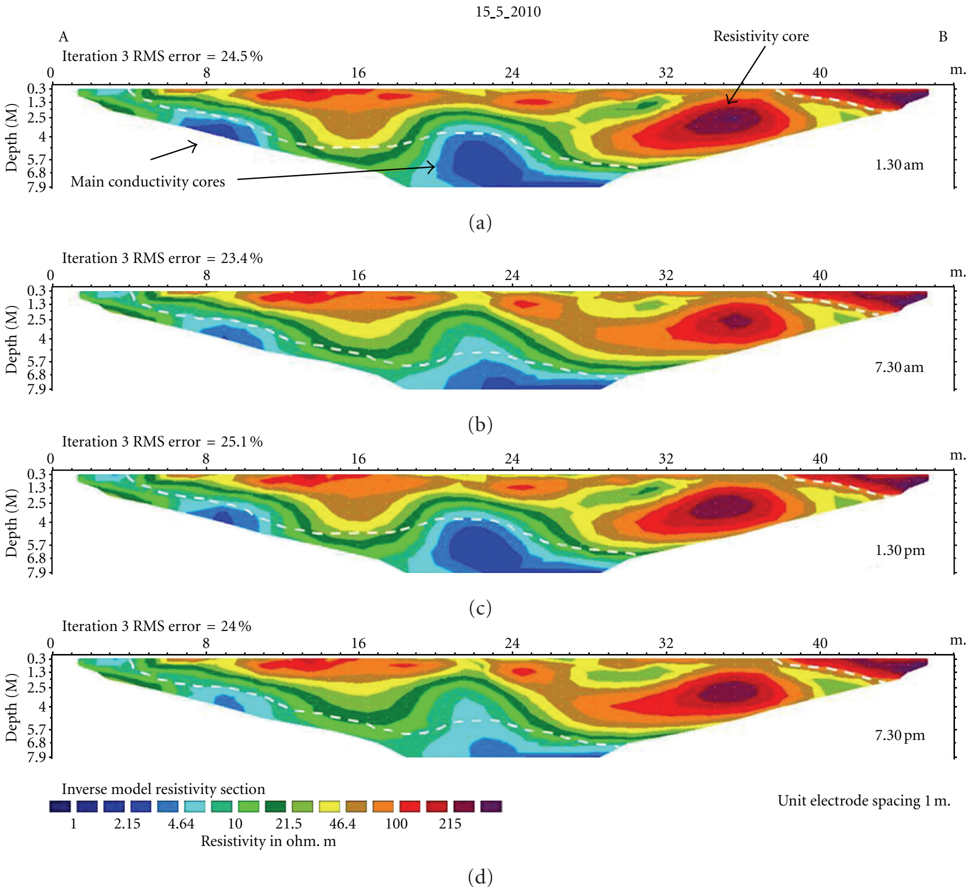


FIGURE 9: ERT related to the 15/05/2010 daily cycle of acquisition.

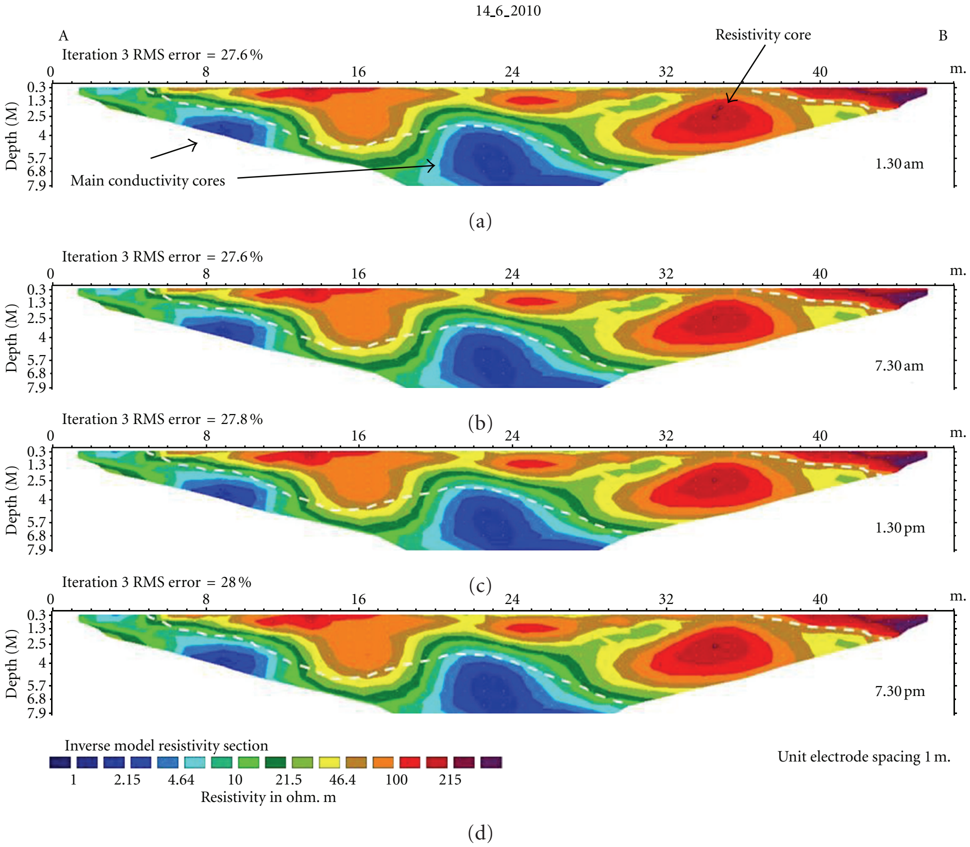
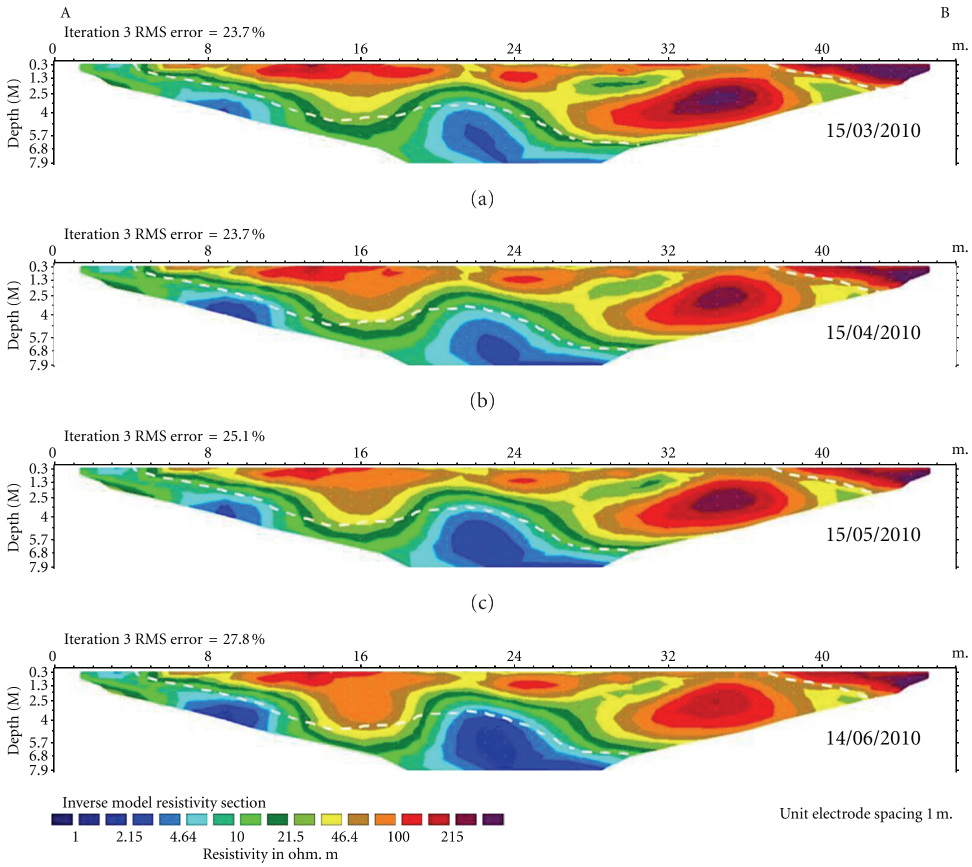


FIGURE 10: ERT related to the 14/06/2010 daily cycle of acquisition.



(a)

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Figure 11: ERT performed in different days with an interval of one month; it is possible to observe the low change in resistivity during all the studied period.

resistivity values: a shallow zone, 2.5 m depth, with higher resistivity values ($50 < \rho < 300\,\Omega$m) distributed all along the profile, and a deeper one with the bulk of lower values ($2 < \rho < 10\,\Omega$m) concentrated in two main conductivity cores. A main central core with a thick of about 4 m and a smaller one in the left side of the tomographies, about 3 m deep. Moreover, by the extremity B of the tomography is evident a high conductivity layer, probably associated with the bedrock, while in the right side of the tomographies is present a large resistivity core.

Moreover, the low change in resistivity is also observed during the entire studied period (March 2010–June 2010). Figure 11 shows the comparison between the third acquisitions of each daily cycle: a general increase of conductivity in the central and right portions of the tomographies is evident, but the distribution of the resistivity values is similar for all the acquisitions.

In order to verify this resistivity distribution in the subsoil, a furthermore analysis was carried out to quantify the size of change ($\Delta\rho$) during the entire period.

In particular, the resistivity differences between the first acquisition (15th of March 2010) and the last acquisition (14th of June 2010) have been calculated, with a time interval of four months. All analyses and pseudosections have been performed by using the SURFER 8 of the Golden Software, Inc.

Variations has been calculated by (1) with respect to the acquisition of ρ_0 at time T_0 (15th of March 2010):

$$\Delta\rho = \frac{\rho_1 - \rho_0}{\rho_0}. \tag{1}$$

Figure 12 shows that the whole section is interested by negative resistivity differences, with values close to 0. This behavior seems to confirm that not important variations occurred during the entire period. Then, the same analysis was carried out in a shorter period, from the end of April 2010 ($T_0 = 28/04/2010$) to the end of May 2010, interested by intense rainfall. This analysis has demonstrated that in a short period the resistivity changes are bigger and well distributed in the whole section (Figure 13).

Pseudosection of the differences shows a variation close to the zero in the shallow layers, except some small positive variations observed in the right side. The remaining portion of the pseudosection is affected by negative variations with a range included between 0 and $-0.2\,\Omega$m, implying an unimportant increase of conductivity. Instead, resistivity differences calculated at T_2 and T_3 show an opposite behavior, with a more emphasized positive variation in the central core

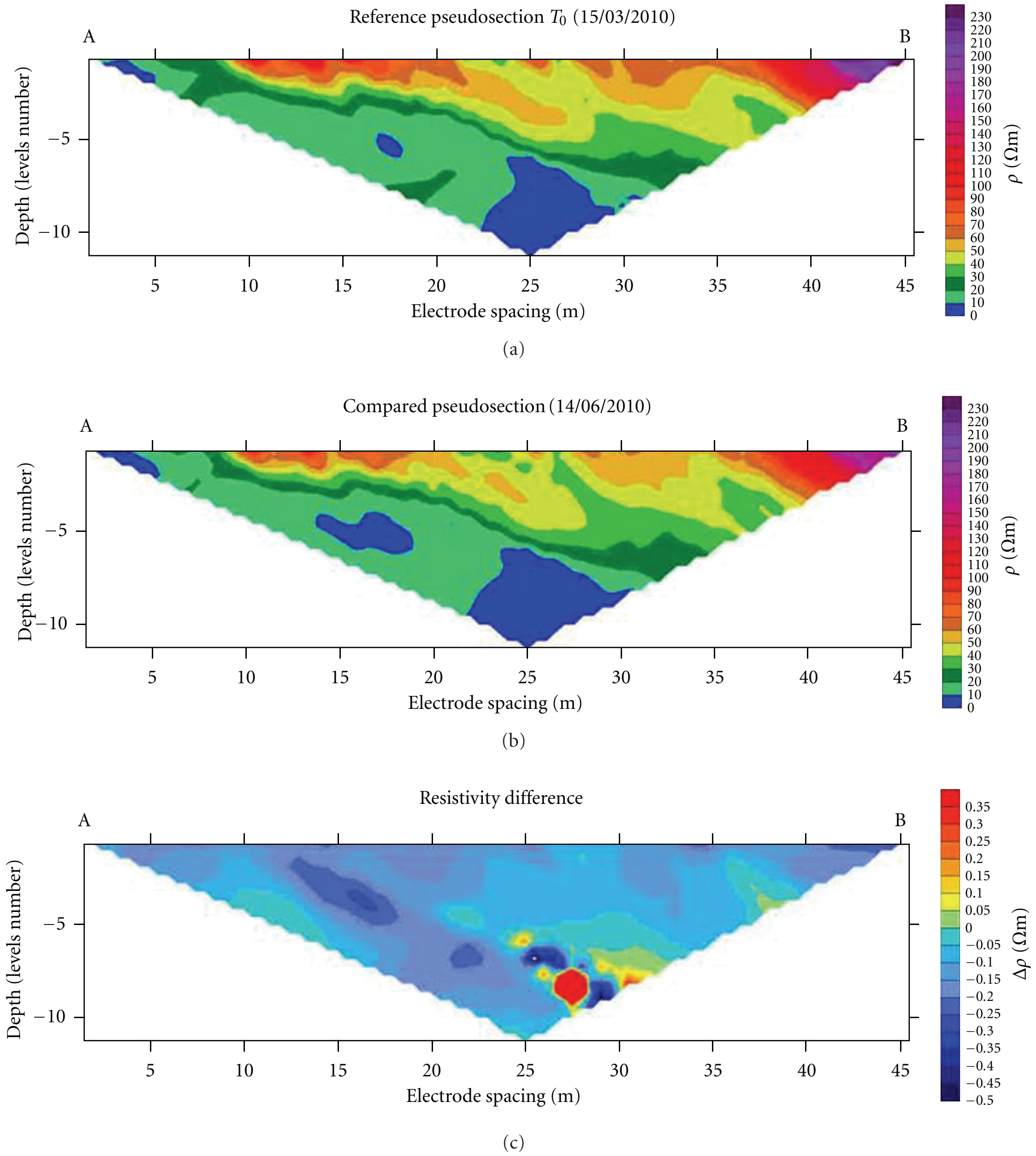

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Figure 12: Resistivity differences calculated with respect to a fixed time T_0 (15/03/2010). No important resistivity variations are observed.

of the pseudosections and negative variations in the shallow layers (Figure 13). Probably acquisition of 16th of May 2010 (T_2) has been conditioned by the intense rainfall of two days before, explaining the shallow variation or resistivity. The electrical state of subsoil seems to remain the same also in the following day, as shown by the pseudo-section referred to the acquisition at time T_3; even if not interested by rainfall, data acquired in the 27th of May 2010 has been probably conditioned by the distribution of rainfall occurred during the week before.

Whatever, starting from July 2010, the frequency of acquisition has been changed in order to emphasize the possible resistivity variations within a day.

5. Comparison between Soil Moisture and Resistivity

To verify if the resistivity variation is related to the variations of water content in the subsoil, the resistivity trend has been also compared to TDR data. In particular, resistivity and TDR data acquired at the same depth (1 m and 1.5 m) have been considered. In some cases, soil moisture has shown a behavior opposite to resistivity, confirming that resistivity variation in the subsoil is influenced by water content. To obtain a good agreement between resistivity and TDR data, acquisition frequency of TDR has been set as similar to the resistivity one, starting from 2 am (GMT + 1).

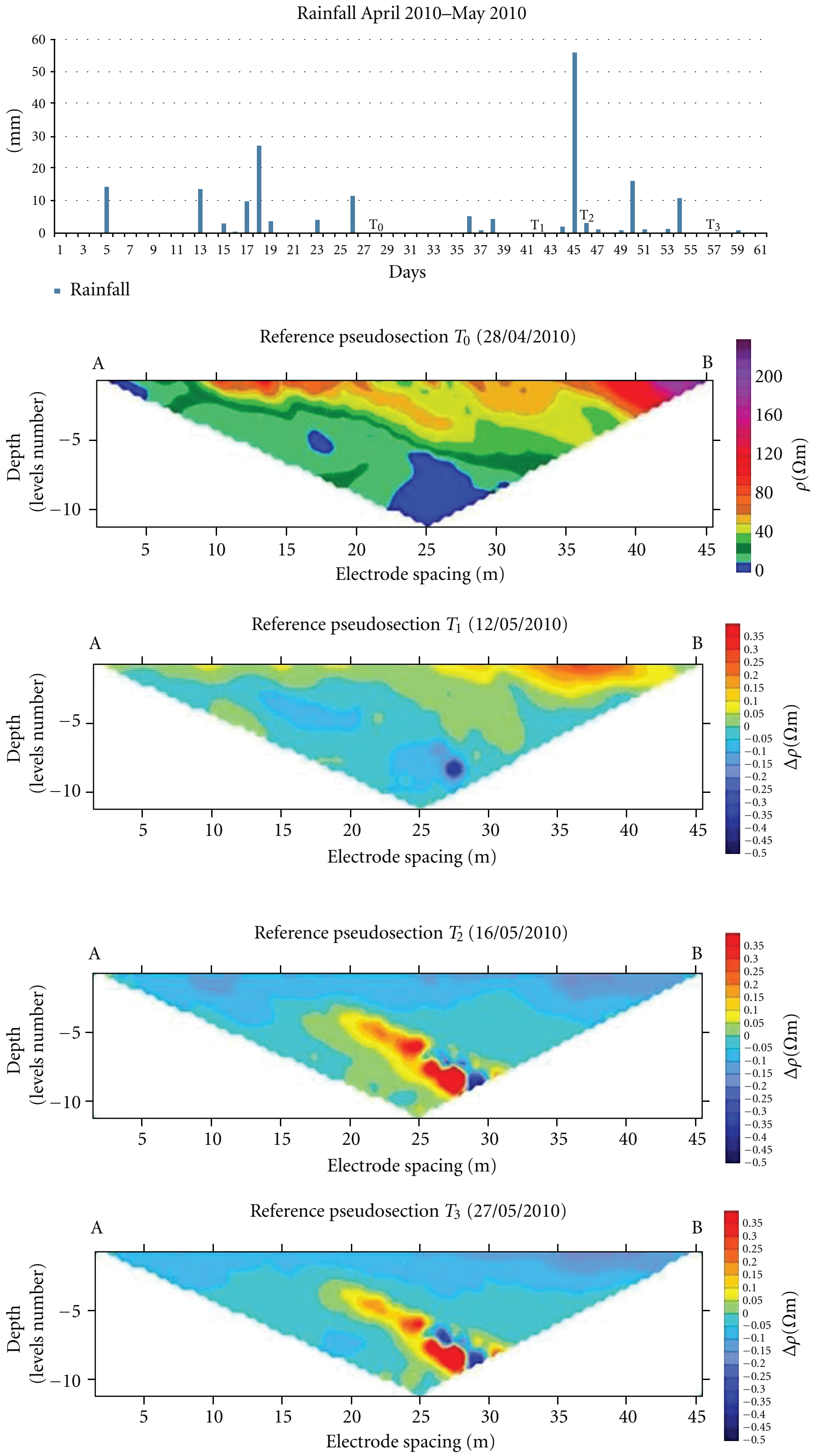

FIGURE 13: Resistivity differences calculated with respect to a fixed time T_0 (28/04/2010). Differences are referred to three days of May 2010, chosen after intense rainfall.

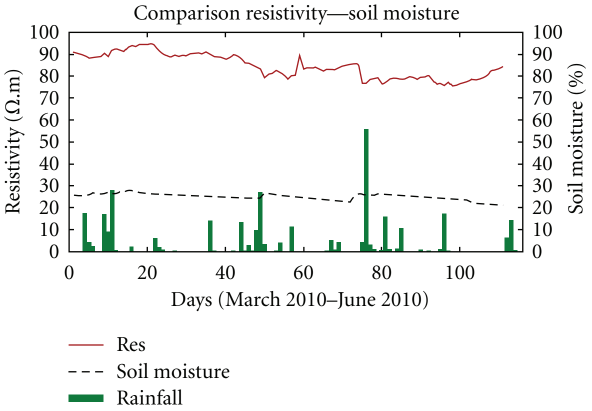

Figure 14: Comparison between Resistivity and TDR data acquired at 1 m depth, in correspondence of the 14 electrode.

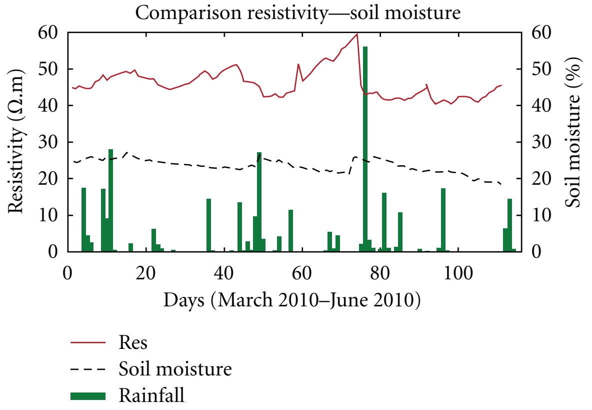

Figure 15: Comparison between Resistivity and TDR data acquired at 1 m depth, in correspondence of the 35 electrode.

Furthermore, also rainfall has been compared to TDR and resistivity, to understand how much the trend of the two parameters has been conditioned by it.

Figure 14 shows the comparison between resistivity and soil moisture values acquired at 1 m depth, equivalent to the 2nd level of the pseudo-section, in correspondence of the 14th electrode.

Fluctuations are present, interesting a range of values included between 75 Ωm and 91 Ωm. Instead, variations of soil moisture are smaller, included between 23% and 27%.

It is possible to observe that soil moisture and resistivity show a similar trend, even if in correspondence of some rain events an opposite behavior occurs. So it seems that the two parameters are not really conditioned by the rainfall during the four months, but just by intense spot precipitation periods.

Figure 15 is about the comparison between the two parameters acquired at 1 m depth, in correspondence of the 35th electrode. The trend of the two parameters is similar to the first example of Figure 13, but the opposite behavior of soil moisture with respect to the resistivity is more evident during the entire period.

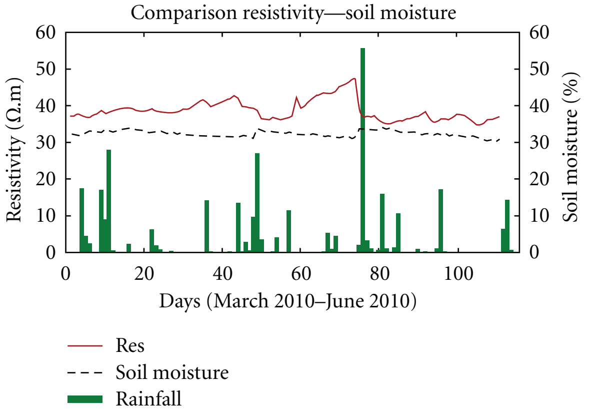

Figure 16: Comparison between Resistivity and TDR acquired at 1.5 m depth, in correspondence of the 35th electrode.

Also in this case the two parameters are not conditioned by rainfall during the four months but just in periods interested by intense rainfall.

The last case is about the comparison between two deeper points 1.5 m deep (3rd level of the calculated pseudosections), always in correspondence of the 35th electrode (Figure 16).

Range of resistivity is included between 38 Ωm and 50 Ωm, while soil moisture has a mean value of 30%. So, a general decrease of the resistivity values has been observed; at the same time, soil moisture percentage remains the same during the four months. A bigger number of events conditioned by the rainfall are highlighted. It has been observed that the two parameters evolve rapidly at the same time and that at this depth the variations of the two trends are more correlated than other shallower cases.

6. Conclusions

The prototype monitoring system has been developed in order to create a powerful tool to highlight the resistivity changes connected with the changes of water content in the first layers of the subsoil, within a landslide body. The real aim was to indirectly determine a preliminary estimate of the water content in an area affected by hydrogeological hazard.

Preliminary ERT have not shown great differences between the first and the last acquisition during the day, confirming the stability of the signal. Also the calculated resistivity differences between the first and the last acquisitions seem to confirm that resistivity is not subjected to big variation during the analyzed period, showing a negative distribution of values, close to 0. Instead, analysis in shorter period has demonstrated that the size of resistivity differences is bigger and well distributed in the whole subsoil section, perhaps conditioned by the intense rainfall period. Whatever, from the data trend analysis, the effect of precipitations is evident. TDR and resistivity trend comparison confirms that there is a decreasing of resistivity in correspondence of soil moisture growth, but this change seems to be stronger when intense precipitation periods occur.

Next step to confirm these preliminary results will be the statistical analysis of resistivity data along a period of 1 or 2 years, to understand if the fluctuation of values is strictly connected to the change of season. Besides, statistical results will be compared to the pluviometric data and to the soil moisture behavior, in order to obtain a more detailed description of the hydrogeological conditions of the area.

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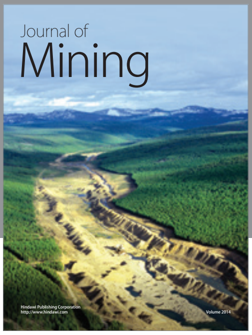

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