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CONVENTIONAL GEOPHYSICAL SURVEYS FOR LANDSLIDE INVESTIGATIONS: TWO CASE STUDIES FROM ROMANIA

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Abstract: A combination of geophysical methods 2-D resistivity (ERT) and ground-penetrating radar (GPR) were applied in order to gain some information about the thickness and the internal structure of two landslides from Romania, in the Lipovei Hills and Apold Couloir (Transilvanian Tableland). In general, all the electrical resistivity data provide useful information on the geometry of the landslide body, lateral extension, but it is also really practical to identify the sliding surfaces, to estimate the thickness of the slide material or to highlight the areas with high water. In this study, the electrical resistivity data were acquired along the same profiles as the GPR surveys by using different electrodes arrays in order to surprise the internal characteristics of the investigated landslides. All the 2-D ERT profiles were completed using GPR data but sometimes the GPR results were affected by strong signal attenuation and it was almost impossible to obtain reliable information to compare them. Despite this drawback, some good results for the application of GPR method on landslides were obtained. It yielded useful information especially on shallow landslides when the radargrams were able to identify the main scarp or the main steps of the landslide. The tomograms and radargrams offers the possibility of correlating internal structure with detailed morphological elements as furrows, ditches, steps, benches, mounds, and microdepression, achieving detailed images of the internal structure of each investigated landslide.

Keywords: 2D resistivity, Ground-penetrating radar, landslides, Romania;

1. INTRODUCTION

In recent years, application of geophysics for landslide studies has widely increased, especially for near-surface exploration of landslide areas marked by a complex geological setting. According to McCann & Forster (1990), geophysical methods can provide the necessary information for hazard assessment of landslides. This considerable attention it is due to a significant progress, in the last 10 years, for some geophysical methods such as Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR). Landslides are complex geological slope process with a high socio-economical impact and their investigation usually requires a multidisciplinary approach for a better understanding of their specific triggering factors and to find out more information on subsoil characteristics. Moreover, this kind of investigations requires more detailed field data and a simple surface investigation such as landslide mapping is not enough to gain knowledge about subsurface, the thickness and internal structure of the landslide. Those aspects are really important when you are dealing with landslide hazard and it`s good to have more information regarding the structure of sliding masses and the movement patterns. The technological progress for both ERT and GPR methods regarding equipment improvement, post-processing algorithms and software seems to be exactly what the landslide investigations needed to solve the problems related to the slope movement in terms of flexibility, low cost, fast and non-invasive data acquisition (Jongmans & Garambois, 2007). More importantly, using the geophysical methods to investigate the subsurface structure, will provide in a short time more 2D data about the internal structure of the landslide comparatively with the traditional techniques (e.g. drillings) that are very time-consuming, very expensive and provide only point information of the subsoil (Sass et al., 2008).

In situ applications of ERT and GPR methods have been demonstrated to be precise recorders of physical parameters of the subsoil, thus the main characteristics of landslides such as geometry, internal structure and composition of the sliding mass, water content, failure surface, physical properties of landslide material, the marks and characteristics of past landslide events can be underlined in this manner (Barnhardt & Kayen, 2000; Batayneh & Al-Diabat, 2002; Lapenna et al., 2003; Bichler et al., 2004; Lapenna et al., 2005; Friedel et al., 2006; Otto & Sass, 2006). In terms of shallow and near-surface investigations, ERT and GPR methods has become an important and useful tool, with significant changes, that increase the field quality of the information obtained for landslides measurements. The most frequently used and one of the standard methods in the study of affected areas by shallow landslide is the resistivity method because this is very useful to determine the characteristics mentioned above (Caris & Van Asch, 1991; Bogoslovsky & Ogilvy, 1997; Havenith et al., 2000). Due to the fact that ERT can solve the problem of lateral resolution make this method to be more appreciated through geophysical methods and reveals a great heterogeneity of landslide material (Bell et al., 2006; Wetzel et al., 2006) or it can be applied on the monitoring of groundwater flow in landslides mass (Suzuki & Higashi, 2001). The literature outlines some good examples of papers that have studied the application of geophysical methods on landslide processes. Since 2000 a lot of papers dealing with the application of 2D ERT for landslide investigation have been published and presented their results and improvements of the method. Thus, there are case studies focused on complex landslides (Perrone et al., 2004; Park & Kim, 2005; Colangelo et al., 2008; Pánek et al., 2008), on translational or rotational slide (Meric et al., 2005; Drahor et al., 2006; Perrone et al., 2006; Lee et al., 2008; Schrott & Sass, 2008; Bekler et al., 2011; Shan et al., 2013). This technique is based on measuring the electrical resistivity and can provide 2D and 3D images of its distribution in the subsoil (Perrone et al., 2014). This parameter is very sensitive to the mineralogy of the particles, the porosity and the ground water content (Reynolds, 1997; Park & Kim, 2005; Bievre et al., 2012).

GPR is an electromagnetic method recently used by several authors for landslide investigation during the last ten years due to its light instrumentation, high resolution and its sensitivity to dielectric, electric contrast and particularly to water content. However, there are severe limitations that are decreasing the successful application in landslide areas, as attested by the low number of case studies on landslides to date. One of the most significant drawbacks is that the GPR signal is highly attenuated in high conductive formations (Jongmans & Garambois, 2007), like clay deposits. Despite these, in international literature there are some case studies with important contributions in this research field, regarding the possible slip surface (Bichler et al., 2004), monitoring the rock walls considering the risk of a rock fall (Roch et al., 2006), internal structure of two large seismically induced landslides (Barnhardt & Kayen, 2000).

Although geophysical methods, especially ERT, are a common topic for landslide investigations in many countries, such studies are almost lacking in Romania. In Romania the study of applied geophysics in landslides is to be mentioned (Popescu et al., 2014) with special issues on ERT approaches, (Maftei et al., 2008) with some seismic investigation in an area affected by landslides, (Dobrescu et al., 2011). The main aim of this study is to obtain information on the landslide structure, water detection within the slip mass, on the lateral and vertical extent of two landslide masses (L1 and L2) from different study areas. Secondly, it was tested the suitability of various geophysical methods on landslide affected area. Thirdly, it was tested different array configuration of the electrodes to highlight their utility. Another aim of this research was to find out whether GPR can contribute to subsurface information in an area affected by landslides. Final results will be the basis for slope stability analysis and the preparation of some future landslide hazard maps and also will be used for further comparative studies based on traditional techniques to investigate subsurface structure, for example drillings.

2. STUDY AREA

Geophysical methods in this study were carried out in two different areas affected by landslides, Buzad (The Lipovei Hills) and Cunța landslide (Apold Couloir).

Buzad landslide (L1) is located near Buzad village, Timiș County (Fig. 2), a hilly area with altitudes exceeding 300 m. The L1 landslide area has an approximate extent of 3600m². Lithology consists of Pannonian deposits (clays, sands, marls, gravels) from Western Foothills, a relief unit with numerous rotational and translational slides of different size and age (Popescu et al., 2014). The average annual temperature is about 10°C and average rainfall ranges between 700-800 mm per year. This landslide is a shallow translational landslides (according to the classification of (Varnes, 1978), with a 90 m length and 40 m wide, reactivated in 2006. The landslide can be divided into three parts: main scarp, transport zone and front of landslide. Most part of the landslide body was scraped by an important number of landslide furrows and covered with grasslands on gentler foot slopes or slope terraces and shrubs on the bottom of the toe. Today, some parts of the morphological landslide characteristics can be observed in the field (e.g. the crown, main scarp-with an amplitude up to 2.5 m in 2007, main body, transverse tension cracks, toe area). Since its first reactivation the landslide body has undergone many transformations as a result of slope movement. Nowadays, the landslide area is in a morphodynamic steady (Popescu et al., 2014).

Cunța landslide (L2) is a shallow rotational landslide, according to the classification of Varnes (1978) triggered in 2010 that is supposed to have two triggered zones. L2 landslide site is located in Apold Couloir (Fig. 2), a relief unit affected by landslide processes of different size and age, making this unit a very complex area characterized by great instable slopes. The regional geology of the Apoldului Couloir is characterized also by Pannonian deposits, yellow sand, clay and marl features. The topography of this study site is gentle (10-15°), greater values corresponding to some landslide scarps, as the L2 slide. Specific to this region is the presence of large areas defined by instability where the most common are the landslide processes due to old landslides that easily can be reactivated when is a suitable geological layer, a high amount of precipitation and a lack and/or poor vegetation blanket. For L2 slide it can be distinguished the typical micromorphology of the landslide: the crown, scarp, landslide body, toe and the furrows being very well defined. At the Cunța site was observed a cvasicircular form of the scarp with a 25 m length and a ranging width between 20 – 30 m, the main body of the landslide not exceeding the 75 m value. On gentler slopes of the L2 slide grasslands can be found both on the upper part (Fig. 1) and lower part.

Figure 1. L2 slide recent reactivations

Today, some parts of the landslide are more visible in the upper slopes which seems to be recently reactivated than in the lower part, where the landslide body and the toe seems not to have changed since the initial triggering. Thus, the downstream section of the slope between 311 and 301 m represents the most stable part of the slide unlike the upstream slopes.

The Cunța landslide lies between altitudes 325m and 301 m, but the signs of surface movement could be observed between 325 m and 311 m a.s.l.

3. METHODOLOGY

The study sites in Buzad and Cunța were investigated using two geophysical methods ERT (Electrical Resistivity Tomography) and GPR (Ground-Penetrating-Radar). These methods were applied to achieve more comprehensive 2D subsurface information and for a better understanding of the landslide process. The geoelectric and electromagnetic measurement results were also compared to see whether ERT or GPR is more appropriate for landslide investigations.

2D ERT investigation was, for landslide L1 and L2, the main and the first approach for subsurface data acquisition. The Electrical Resistivity Tomography (ERT) is a geophysical method that can provide 2D images of the distribution of the electrical resistivity in the subsoil (Perrone et al., 2014). The analysis and interpretation of these tomograms allows the identification of resistivity contrasts that can be found in some area due to the lithological pattern of the terrains and the water content variation. Geoelectric measurements are based on the injection of a constant current into the ground through two current electrodes and measuring the resulting voltage differences between another two potential electrodes at the surface (Sass et al., 2008). The mathematical combination between electric currents and voltage values provides the apparent resistivity values. To determine the subsurface resistivity characteristic for different zones or layers from investigated areas an ”inversion” routine of the measured apparent resistivity values must be carried out. This resistivity inversion was achieved using RES2DINV software (Loke, 1997), based on the smoothness constrained least-square method proposed by (Loke & Baker, 1996) considering a quasi-Newton optimization technique. This algorithm assumes that the subsurface is divided into regular blocks, whose number corresponds to the number of measurement points (Colangelo et al., 2008). The result obtained gives data on spatial averages of subsurface resistivity in a 2-D section (Sass et al., 2008).

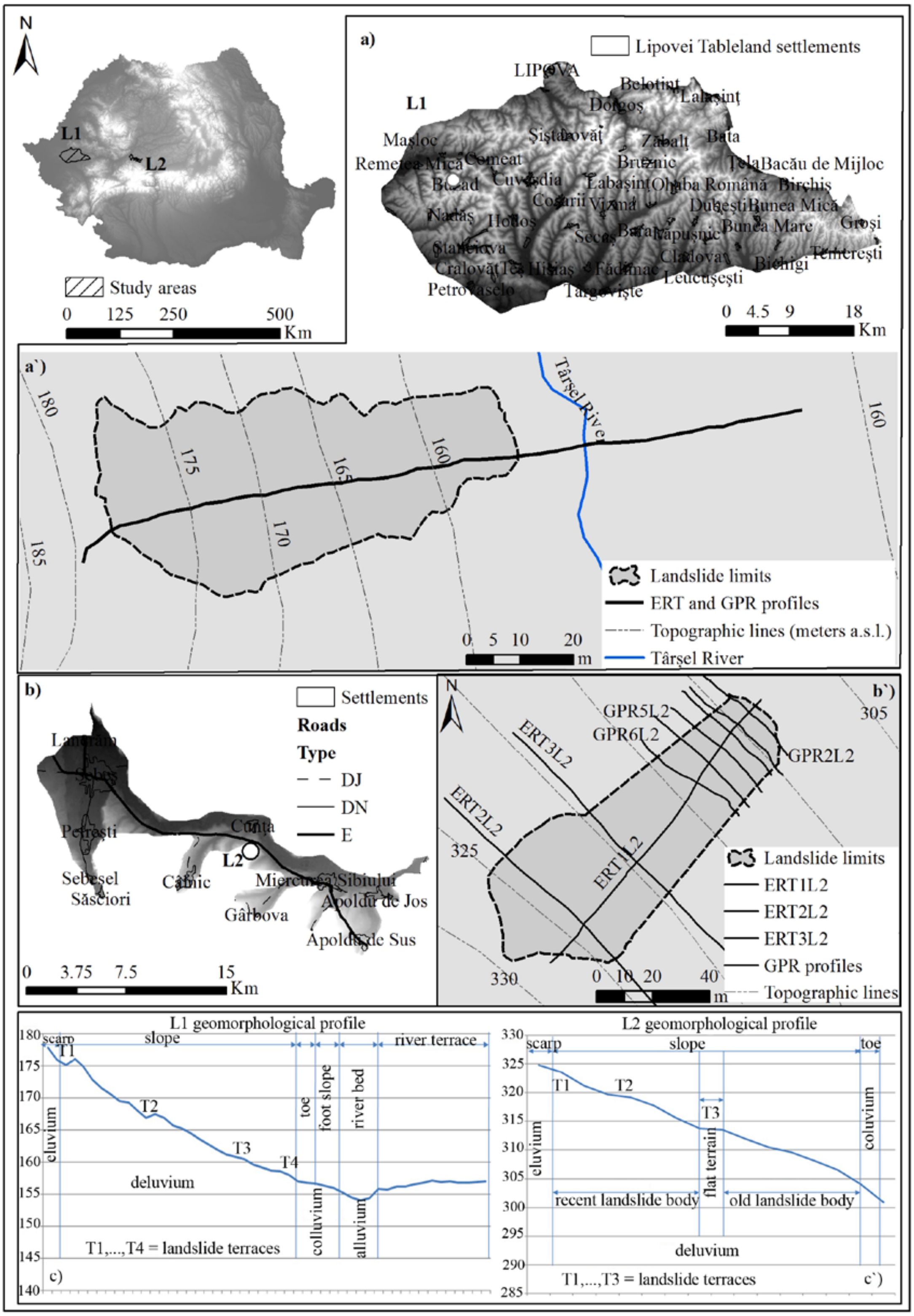

Figure 2. Location of the study area (a and b); geophysical measurements sketch (a` and b`); geomorphological profiles for study areas: (c and c`)

Using the mentioned software is very useful because allows the inclusion of data on the local topography for data processing (Bell et al., 2006). To evaluate the fit of the resistivity model obtained, the root square error (RMS) has been calculated, thus achieving the percentage difference between the measured values and those calculated. According to (Perrone et al., 2014) the similarity between the field data and the estimated data model is higher when the error is lower.

The geoelectric measurements were undertaken using a GeoTom 2000 unit equipped with 50 electrodes. This is a multi-electrode data acquisition system that has greatly improved the speed and reduces the cost of acquiring field data, thereby achieving a large volume of information. In order to highlight vertical and horizontal changes or structures of the landslide, Wenner, Schlumberger and Dipole- Dipole arrays have been acquired for each profile. In general, the choice of electrodes arrays depends a lot on the subsoil conditions, the depth of investigation, the horizontal data coverage, the sensitivity to vertical and horizontal changes in the subsurface resistivity and the signal strength (Loke, 1999). For L1 site it has been used a total number of 50 electrodes, unlike L2 site where only 25 electrodes have been used due to the presence of the electricity wires closed to the triggering zones and the road in the lower part. With respect to the aimed penetration depth and resolution, a unit electrode spacing of 3 m for L1 and 4 m for L2 has been applied, which amounts to a total profile length of 147 m respectively 96 m for longitudinal profiles. Same 4 m electrodes spacing was used for cross sections lines yielding to a 96 m length of each profile. The penetration depth generally ranged between 15 and 20 m (around 1/6 of the ERT survey line). In the field were measured resistivity data for two longitudinal profiles and for two transversal profiles. Both cross sections were carried out for the L2 slide and provide significant results for the recent reactivation of the landslide in the upper part.

Ground Penetrating Radar (GPR), another geophysical method applied to L1 and L2 landslides is based on electromagnetic measurements. The principle of the GPR geophysical method is based on a short high-frequency electromagnetic wave emitted from a transmitter antenna into the ground, reflected at subsurface objects and inhomogeneities. The travel time of the reflected waves is subsequently recorded by a second antenna, known as receiving antenna. The propagation of a radar signal depends mainly on the electrical subsurface materials (Milsom, 2007). Applying this method involves a simple task for the operator, the whole array being moved along a survey line, thus creating a 2D section of the investigated subsurface. The depth range of GPR is limited by electrical conductivity of the ground, the transmitted center frequency and the radiated power. The frequencies range from 10 to 2500 MHz (depending on the system), as well as depth penetration whose values are between 0.5 m and 50 m. As conductivity increases, the penetration depth decreases. Lower frequencies can reach depths up to tens of meters (e.g. 100 MHz can travel up to 15 meters) with a resolution of tens of centimeters, while higher frequencies can give a resolution of centimeters but up to depths of several meters (Sharma, 2002).

Compared with the geoelectrical measurements, a very common tool for subsurface investigation of landslides, GPR presents some limitations that decrease the potential of the method for landslide investigation. The first major obstacle for the use of this instrument in landslides environment is that GPR signals are highly attenuated in high conductive formations as it happens for wet and clayey subsurface of the landslides. Thus, for these types of layers a strong attenuation of the radar waves and a limited penetration depth will be characteristic (Sass et al., 2008). A dramatically decreasing of the penetration depth is also caused by diffractions due to heterogeneities like fractures and blocks (Jongmans & Garambois, 2007). Despite these conditions, in this study it was tested whether GPR can contribute or not to improve the methods of getting subsurface information in landslide areas.

For this investigation, a Malå Geoscience ProEx radar system was used. The GPR device was equipped with a 100 MHz Rough Terrain Antenna. This type of antenna is designed as a flexible ,,snake” like that provides an easily handling in the rough terrain without affecting ground contact and providing optimum results for difficult investigation environments. An 83 m longitudinal profile was carried out for L1, on the same survey line as ERT profile. As for L2 investigation site there were measured one longitudinal profile of about 100 m length and 8 cross-profiles across the landslide surface (Fig. 2). The radargrams were processed using the ReflexW software (Sandmeier, 2012). Within this program several correction (e.g. substract DC-shift correction, static correction, subtract mean (dewow), a gain function filter) were applied.

4. RESULTS AND DISCUSSIONS

In this work, geoelectric measurements (ERT) were performed at a total of four profile lines along the axis of the landslide body and transverses to it to get more detailed information on the depth and internal structure of the landslide deposits (Fig. 2).

The calculated inversion models show an immanent error (RMS) that ranges between 3.1% and 6.3% for L1 profiles respectively, 3% and 4.3% for L2 profiles. In order to obtain such a RMS value a maximum of 5 iterations has been used. Thus, the data for L1 and L2 tomography profiles are indicating good and reliable results.

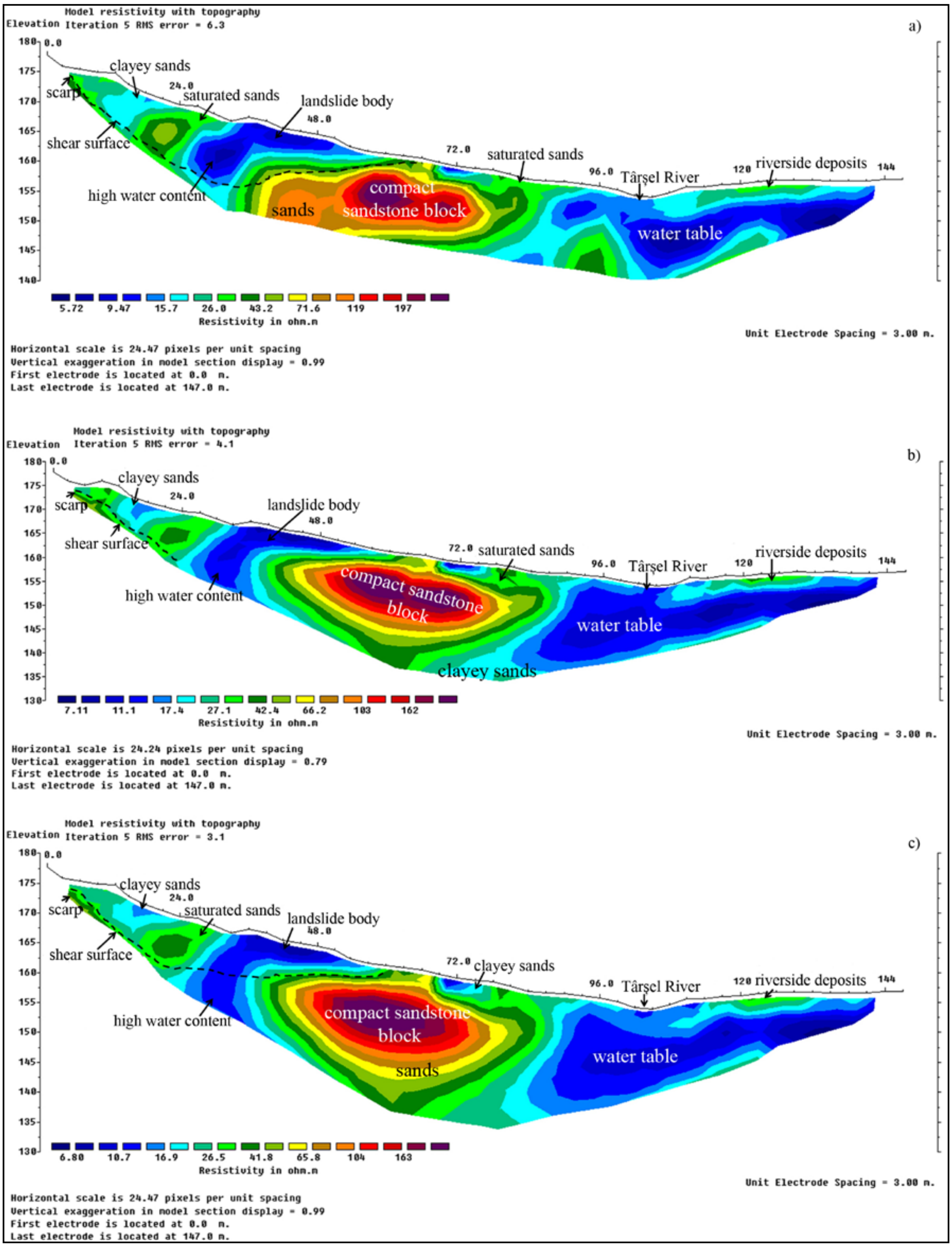

Figure 3. Different array configuration for longitudinal ERT profile (L1 study area): a) Schlumberger; b) Wenner; c) Dipole-Dipole

The higher value of RMS from L1 slide area it could be explained by some electrodes contact problems which induced some noise to the data, but it didn`t affect the data interpretation.

Profile ERT 1L1 (Fig. 3) reveals good results concerning the depth and the lateral extent of the landslide, estimating the thickness of sliding material, locating the possible sliding surface. On the whole profile length very low resistivity values around 26 Ωm are highlighted, except the middle section where a compact sandstone mass it can be distinguished, with a much higher resistivity than the surrounding clayey sediments and saturated sand layers. In the upper part it could be detected the sliding plane at a depth of 2 to 5 m. Lower resistivity values in the upper slopes also revealed an advanced weathering near the surface and the landslide body that reaches up to 5 m in thickness. The landslide body is represented either by marls, clay, saturated sands or clayey sands. It is assumed that between 33-51 m and the middle of the ERT 1L1 profile lower resistivity values are explained by areas of high moisture content that coincides in the field with the presence of some furrows and bushes crossing the profile. Further down slope, there appears the second uniform layer that represents very low resistivity values. This it could be associated with the Târșel River presence and water table level. On the right riverside terrace 42 Ωm resistivity values are indicating some riverside deposits consisted in saturated sand and clayey sands.

Longitudinal ERT 1L1 profile shows different depth investigation (Fig. 3) depending on electrode arrays configuration. The higher depth was achieved for Dipole-Dipole configuration (23-25 m) and the lowest for Schlumberger array (14-15 m). Despite this drawnback Schlumberger array seems to be moderately sensitive to both horizontal and vertical structures, while Dipole-Dipole is more suitable for the investigation of vertical boundaries. Wenner electrodes configuration is relatively sensitive to vertical changes in the subsurface resistivity below the center of the array. Geoelectric profiles were performed along cross-sections of the slide L2 to determine the internal structure of the landslide. We used a survey line of 96 m, which enabled a penetration depth of approximately 18 m for longitudinal profile (Fig. 4) and 5-15 m for transversal sections (Fig. 5).

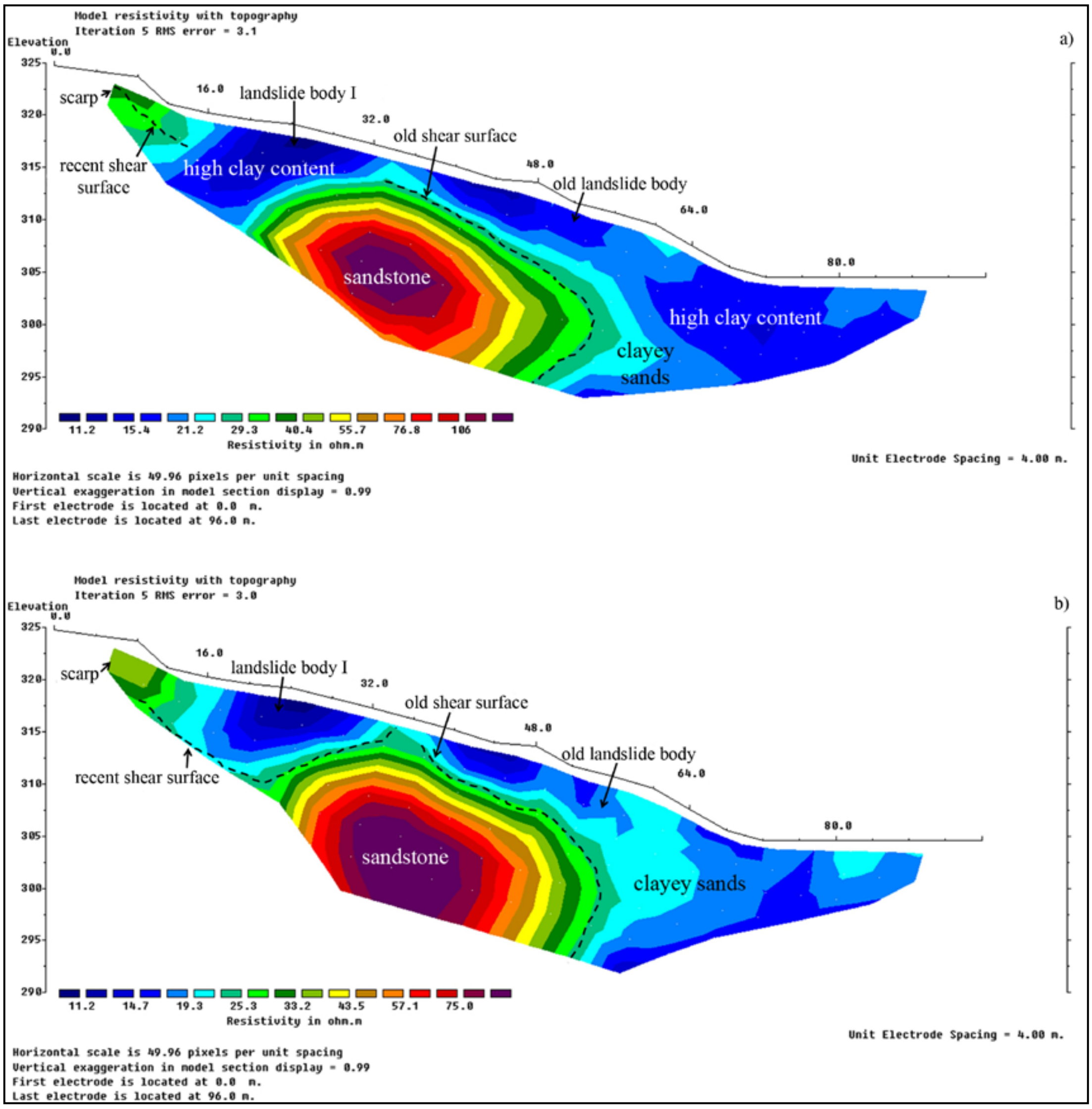

Figure 4. Different array configuration for longitudinal ERT1L2 profile (L2 study area)
a) Schlumberger; b) Wenner

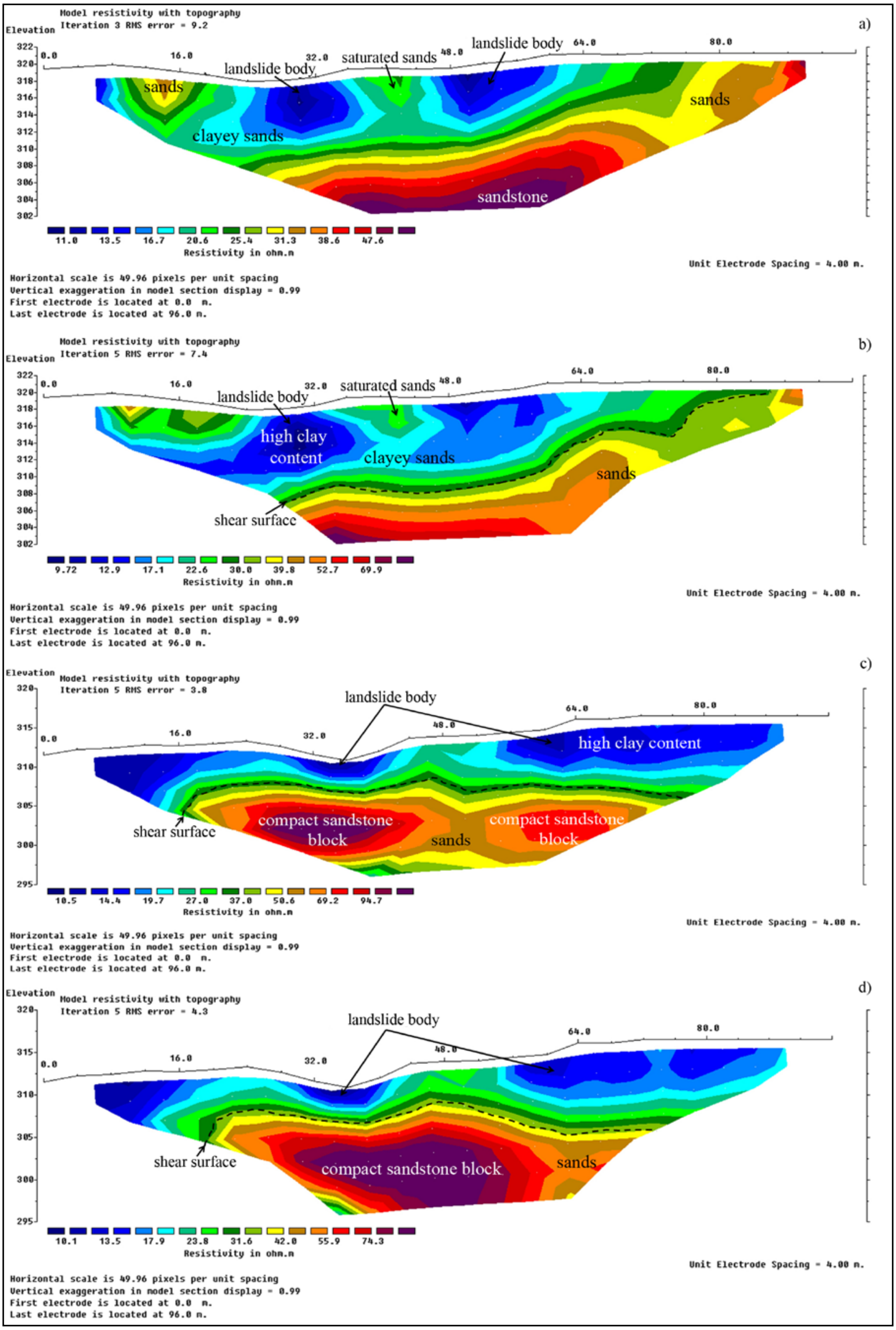

Figure 5. Different array configuration for transversal profiles: ERT2L2: a) Schlumberger; b) Wenner and ERT3L2: c) Schlumberger; d) Wenner

The resistivity model for this study area (L2) can be divided into three different units: a) a very low and uniform resistivity values of about 15 Ωm and 6 m thickness along the profile, except the accumulation zone where this layer becomes larger in lower slopes; b) a very thin layer that corresponds to the slip surface, clearly indicated by lower resistivity 21(Ωm) caused by higher water content or higher portion of clays; c) a layer of up to 106 Ωm at the middle of profile with uniform resistivity values pointing no evidence of landslide activity and a 10 m estimated thickness. The low resistivity anomaly on the whole profile in the first 6 m depth represent the landslide body and consists of high amount of clay and clayey sands and less likely a low-water quantity due to the dry season in the fall of 2014 (October 2014). The lack of water it has been confirmed by the presence of numerous cracks observed in the field on the sliding body.

The upper part of the landslide (the first 32 m) represents some recent reactivation. The results of the cross-profiles ERT 2L2 and ERT 3L2 confirm the interpretation of the landslide body (conducting zones) from longitudinal section. The landslide body was established at a depth of 6 m. The resistant body identified on all tomograms applied for L2 site, is characterized by heterogeneous resistivities with several intrusions in the shape of resistant cores. ERT 2L2 present different landslide body thickness (6-7 m) compared to ERT 3L2, less than 3 m. This difference can be explained by the recent reactivations until the flat terrain from the middle section. By methodological point of view, regarding the various electrode configurations it was found that Wenner array can surprise a better delineating of sliding surface unlike Schlumberger (Fig. 3, Fig. 4 and Fig. 5).

Detailed field work and interpretation of ERT results obtained for L2 study site reveals different geological contexts and tendencies (Fig. 6). This was made based on assumption that various entities like solid bedrock, water, clay, sediments, sands or saturated sands etc have detectable electrical resistivity contrast relative to the host medium (Reynolds, 1997). Generally ERT data field measurements provides an approximate picture of the subsurface resistivity, but it is very useful and necessarily for complex phenomena such as landslides.

GPR measurements were achieved on the same survey line as ERT measurements for longitudinal profiles and it had been used a 100 MHz antenna. For L2 site nine GPR profiles were applied. For both investigation areas, the GPR results were affected by strong attenuation of the radar waves, therefore the penetration depth values were ranges between 3 m for L2 and 4-5 m for L1 (Fig. 7).

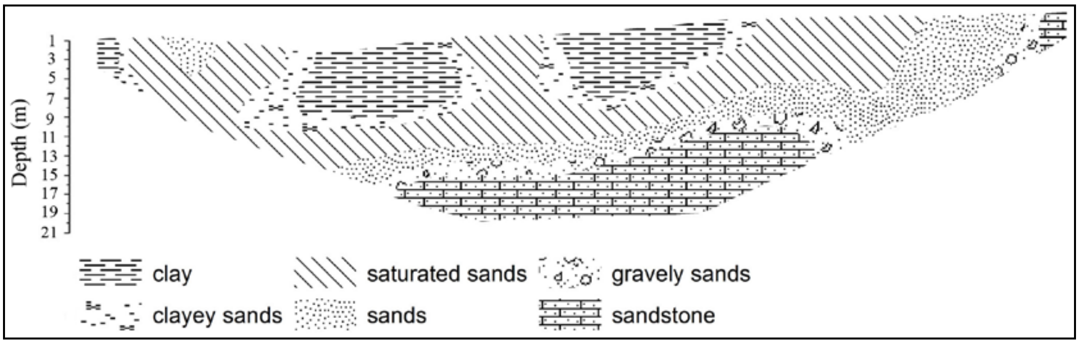

Figure 6. Geological formations for L2 study site according to ERT results

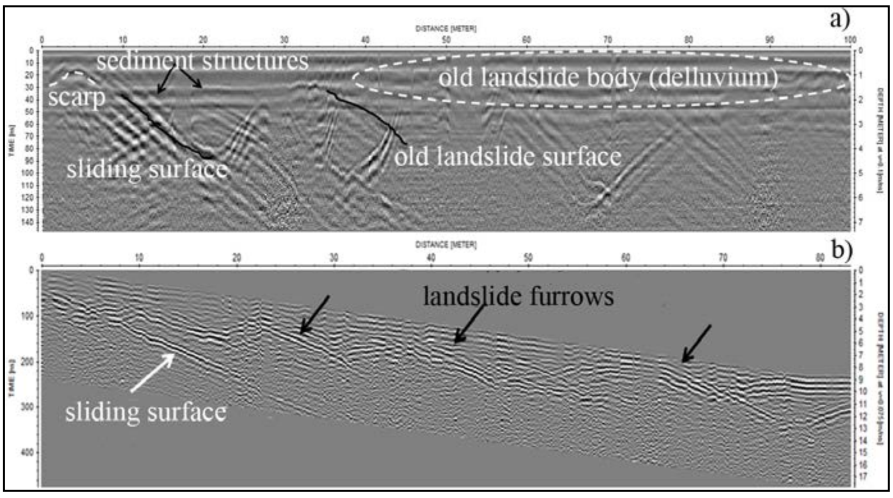

Figure 7. GPR longitudinal profiles: a) GPR1L2; b) GPR1L1

The best results were obtained for longitudinal profiles and for the upper cross-profiles in L2 where the subsurface resistivity was higher. The GPR observations allow detecting different soil structures near subsurface, such as: scarp, sliding plan, main steps, and cracks. After this depth the signal quality decreases due to the highly conductive clay rocks that induced a stronger damping and lead almost all the results to be useless and inconclusive, especially on the lower part of the landslide (the old landslide). Longitudinal GPR profile (GPR 1L2) provides some information about the small depressions filled with loamy sediments.

5. CONCLUSIONS

In this work, two study areas affected by landslides are presented. To investigate, monitor the landslide body and to achieve more comprehensive subsurface information for a better understanding of the landslide process a combination of two geophysical techniques have been carried out, ERT and GPR . This combination provided very valuable information on the Buzad and Cunța landslide structure. Information coming from ERT measurements allowed delineating the main shear surface at a depth of maximum 2-5 m for L1 and 6-7 m for L2. In addition, according to ERT results, the water saturated zones indicated by low resistivities were identified. Moreover, the ERT method was successful in detection of the consolidated and unconsolidated lithologic slide material composition. Comparing with GPR measurements, ERT results allow a more precise definition of structural and lithological interfaces. Thus, the electrical resistivity tomographies clearly defined the clayey deposits involved in the old mass movement, L2 old landslide body, but also involved in recent reactivations, like in the upper slopes of L2 slide and L1 slide.

The interpretation of ERT results turned out to be the best choice to get detailed spatial information on thickness and extent of the slope movement, and in the same time an efficient geophysical tool for preliminary studies on shallow landslides in Romania.

This performance is due to the resistivity contrasts of the shallow heterogeneities which are more easily measured by electrical methods compared to electromagnetical methods applied in landslide areas.

2D electrical resistivity profile shows different depth investigation depending on electrode arrays configuration and on the electrode spacing. The higher depth was achieved for Dipole-Dipole configuration, 23-25 m on L1 and the lowest for Schlumberger array, 14-15 m on L1. Despite this drawnback Schlumberger array seems to be moderately sensitive to both horizontal and vertical structures, while Dipole-Dipole is more suitable for the investigation of vertical boundaries. Wenner electrodes configuration is relatively sensitive to vertical changes in the subsurface resistivity below the center of the array. Lower values were obtained for ERT profiles from L2 where the distance between the electrodes was 4 m comparing with L1 site where it had been used 3 m electrode spacing, a normal situation in relation to the instrument working ways.

Ground penetrating radar (GPR) measurements were affected by a strong attenuation of the radar waves due to loamy sediments, therefore it was almost impossible to gain information below 5 m deeper. Despite these drawbacks, GPR observations allowed detecting different soil structures near subsurface, such as: scarp, sliding plan, main steps and cracks. However, GPR investigations showed that this method is much more limited compared to the 2D resistivity technique for shallow landslide surveys.

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