Geosciences
Geociências

Characterization of Sobradinho landslide in fluvial valley using MASW and ERT methods

http://dx.doi.org/10.1590/0370-44672019730109

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Abstract

Landslides can substantially impact the fluvial systems, which is why the continuous mapping of their extent, evolution and stability assessment is crucial. However, in such environments, material identification (e.g. colluvium) and subsurface characterization by the methods used for geologic mapping and geotechnical investigation is often a challenging task. Thus, these classical invasive methods may benefit from geophysical techniques to enable and enhance our understanding of the subsurface in these areas. To examine such integrated approach, Multi-Channel Analysis of Surface Waves (MASW) combined with Electrical Resistivity Tomography (ERT) were applied on a geomorphologically active fluvial valley in Sobradinho (the Federal District of Brazil). The subsurface materials showed a specific range of resistivity values as dry soil, saprolite, and landslide slip surface. The 1D shear wave velocity (Vs) model showed an increasing trend of Vs with depth at a location away from the landslide mass, while the longitudinal profile (over the landslide) showed an anomalous change in Vs (~ 250 to 400 m/sec). Based on the existing information about the landslide, the ERT appeared to be an effective method over MASW. This study shows how the integration of geophysical data with the geological and geotechnical investigation helps to obtain a more realistic or unambiguous model of the subsurface.

Keywords: fluvial valley; stratigraphic sections; dispersion curve; dipole-dipole array.

1. Introduction

The instability of colluvial slopes, which are usually encountered around fluvial valleys, presents a significant challenge for geohazard risk assessment in many countries around the world, including Brazil. Several studies of this phenomenon have been conducted to understand the mechanism of instability (Ehrlich *et al.*, 2018 and references therein; Hussain *et al.*, 2019a), which can be attributed to different factors and processes that lead to deterioration of the geotechnical conditions as changes of the shear strength and effective stress (Keefer and Larsen, 2007).

In tropical regions, rainfall-induced slope failures are commonly associated with pore water pressure changes due to the water infiltration through the unsaturated soil layer. The sediment movements at the slip surface can also be triggered by the cut at the slope toe on account of the seasonal river erosion, e.g., Sobradinho landslide (Hussain *et al.*, 2019a). In addition, liquefaction caused by a combination of saturated materials and seismic loading can also trigger mass movement in colluvial slopes. Therefore, the correct identification of colluvial materials, as well as geomorphological units, surficial fractures, and cracks (that provide permeable paths to the rainfall water) are crucial for landslide risk assessment around fluvial valleys.

Landslides and other slope instabilities have been traditionally investigated by boreholes and *in-situ* geotechnical tests (Hamza and Bellis, 2008; Mitchell *et al.*, 1978) such as Standard Penetration Test (SPT), Cone Penetration Test (CPT), and Flat Dilatometer Test (DMT). These are accompanied by laboratory tests conducted on samples, such as the resonant column test, ultrasonic pulse test, cyclic simple shear test, cyclic triaxle compression test, and cyclic torsional simple shear test (Bandyopadhyay *et al.*, 2019). However, these investigations provide non-continuous information (limited to the location of the boreholes), as well as having limitations associated with laboratory tests, such as sampling disturbance, unrepresentative sampling, point measurements, and high costs and time.

In this sense, the geophysical methods have appeared as an economic and time-saving approach to supplement the traditional geotechnical *in-situ* testing (Taipodia *et al.*, 2018; Ismail *et al.*, 2019) besides being noninvasive and allowing spatial and temporal investigations. Geophysical methods are based on the physical properties of ground materials. For example, the Electrical Resistivity Tomography (ERT) and the Multi-channel Analysis of Surface Waves (MASW) (which were adopted in this study) are based on the electrical and seismic properties of materials, respectively. ERT has been extensively used for the determination of landslide slip surface and its hydrological characteristics (Kneisel, 2006; Panek *et al.*, 2008; Burda *et al.*, 2013; Dostál *et al.*, 2014; Szalai *et al.*, 2014; Ling *et al.*, 2016; Bran *et al.*, 2017; Kristyanto *et al.*, 2017; Qiao *et al.*, 2017; Carlini *et al.*, 2018; Mita *et al.*, 2018; Kasprzak *et al.*, 2019).

Likewise, there are numerous successful utilizations of the MASW method in the field of geotechnical engineering and environmental studies (Miller *et al.*, 2003; Ivanov *et al.*, 2006; Lane, 2009; Uhlemann *et al.*, 2016; Su *et al.*, 2017; Tábořík *et al.*, 2017). Along with single applications, there are many case studies where joint geophysical techniques have been adopted (e.g., Refraction, Reflection/MASW, and ERT) for the analysis of landslides (Bichler *et al.*, 2000; Grit and Kanli, 2016).

The present study applied MASW in combination with ERT for a landslide site characterization in the Federal District of Brazil, aiming to map the depositional features of the fluvial valley and to characterize the site subsurface. The results were integrated with the existing *in-situ* geotechnical data and geological information. Attempts were made for the determination of the slip surface of the landslide that can be used for volume estimation. In addition, the applied techniques were examined in terms of the sensitivities for differentiating the geomorphological units present in the valley. This study provides insight into several key factors in the geophysical approaches, which can help to develop an improved landslide characterization and slope stability analysis in fluvial areas.

2. Material and methods

2.1 Study area

The Ribeirão Contagem watershed extends over 146 km^2 and is in the northern part of the Federal District of Brazil in the Sobradinho administrative unit. The Maranhão River is the main tributary of the watershed that flows in the north-northeast directions. The drainage and channel densities of the watershed are 5.7 km/km^2 and 32.9 channels/km^2, respectively (Ferreira and Uagoda, 2015). The climate in the area is semi-humid tropical with a rainy summer and dry winter. The mean annual precipitation in the area is about 1,442.5 mm, and it is mainly related to rainfalls. The study area receives a high intensity of rainfall all year round, especially in summer, which affects the degree of saturation and so the geophysical properties (electrical, electromagnetic, and shear wave velocity). The slope chosen for this study is located near a farm in the vicinity of '*Rua do Matto*' (Figure 1). This landslide is an E-W trending rotational earth-slide, having dimensions of approximately 150 m long and about 70 m wide. The landslide has not been studied extensively, so it lacks information about its occurrence and its causes. However, based on the information on the other similar events in the region, it can be said that it was caused by rainfall-induced pore-water-pressure combined with the erosional influence of the Contagem River. The landslide has a scarp in the middle of 2m in height, which was possibly created by the release effects of the bottom flowing Contagem River that eroded the landslide body. The erosional potential of this river is related to rainfall in the surrounding areas, which is quite high during the rainy season (Hussain *et al.*, 2019b).

In the previous geotechnical study, soil samples were collected and analyzed. Accordingly, different geomorphological units were identified: alluvial, colluvial, and landslide (Figure 2). Based on the determined geotechnical parameters, a numerical simulation was performed, which showed a reasonable factor of safety (Braga *et al.*, 2018). In the next geophysical study, Ground Penetration Radar (GPR) profiles were developed along with the locations of the soil sampling points. The amplitudes of electromagnetic waves were used for the differentiation of the geomorphological units. The GPR results showed a good correlation with those of the soil samples (Nunes *et al.*, 2019). Landslide stratigraphy was also obtained as a result of joint inversion of Frequency- wavenumber (f-k) and Horizontal to Vertical Spectral Ratio (HVSR) curves (Hussain *et al.*, 2019d). The ambient noise based (Hussain *et al.*, 2017; Hussain *et al.*, 2019c) and emitted seismic based studies were also applied for monitoring of soil mass movement. In the micro-seismic based studies, two arrays of four sensors were used for the data acquisition. The results indicated the absence of dynamism (internal sliding) in the landslide body and only propagative signals generated by the fluvial process of the bottom flowing river were observed (Hussain *et al.*, 2019b). Time-lapse interferometry was applied at a triangular array of sensors for the study of rainfall-induced fluidization. However, no changes in the material state were found because of the smaller degree of saturation (Hussain *et al.* 2019c).

Figure 1 - (A) Location of Brasilia on the map of Brazil, (B) position of Ribeirão Contagem watershed on the map of Brasilia, (C) The locations MASW (L1, L2, and L3) and ERT (ERT-1 and ERT-2) and E1 soil sampling profiles (P1-P13). Bottom left lithological information taken from a nearby groundwater well (modified after Hussain *et al.,* 2019b). The dotted red line is the hypothetical landslide boundary. Red dots on yellow line show the length of seismic lines.

2.2 Geology and geomorphology

The Federal District covers the eastern part of Tocantins Province. The Brasiliano orogenic event (end of Neoproterozoic, some 570 Ma) that is ranked into five deformational phases, due to which the lithostructural changes occurred in the past. Towards the San Francisco craton, this cycle is characterized as compressive tectonics, which present the first of these four stages with folds and ductile-brittle faults that made both dome formation (the Brasilia, the Pipiripau and Sobradinho domes) as well as structural basin creation (Freitas-Silva and Campos, 1998). The geology of DF has been revised and updated in the form of a new geological map at 1: 100.000 scale. In this new map, four lithological boundaries were distinguished: (i) Paranoá (metasedimentary rocks), Canastra (phyllites), (ii) Araxá (schists), (iii) Bambuí (clayed metasiltites rolled, clay and metasiltites banks) and (iv) Groups and soil or waste shallow colluvial deposits (pedimentary type). These lithological units are present in reverse successions, where the younger lithostructral unit lies below the older ones. The geological setting of the aforementioned succession is mainly related to thrust faulting (Hussain *et al.*, 2017a, and references therein).

The studied area is geologically composed of meta-sedimentary rocks of Proterozoic age that were deformed during the Brasiliano Cycle (650 My) covered by a thick weathering mantle. The Sobradinho Unit, is located in the Ribeirão Contagem Basin, in which low-grade metamorphic sediments of the Paranoá and Canastra groups occur. The Federal District, more specifically its north-central portion, is in the domain of the Tocantins Structural Province, in the Brasília Dobramentos Range where rocks are attributed to the Canastra, Paranoá, Araxá and Bambuí groups of Proterozoic ages (Canastra and Paranoá groups ~1,100 million years old and Araxá and Bambuí groups ~700 million years old). The geology of the area consists of the rocks from Paranoá group (metasedimentary rocks) (Hussain *et al.*, 2017a, and references therein).

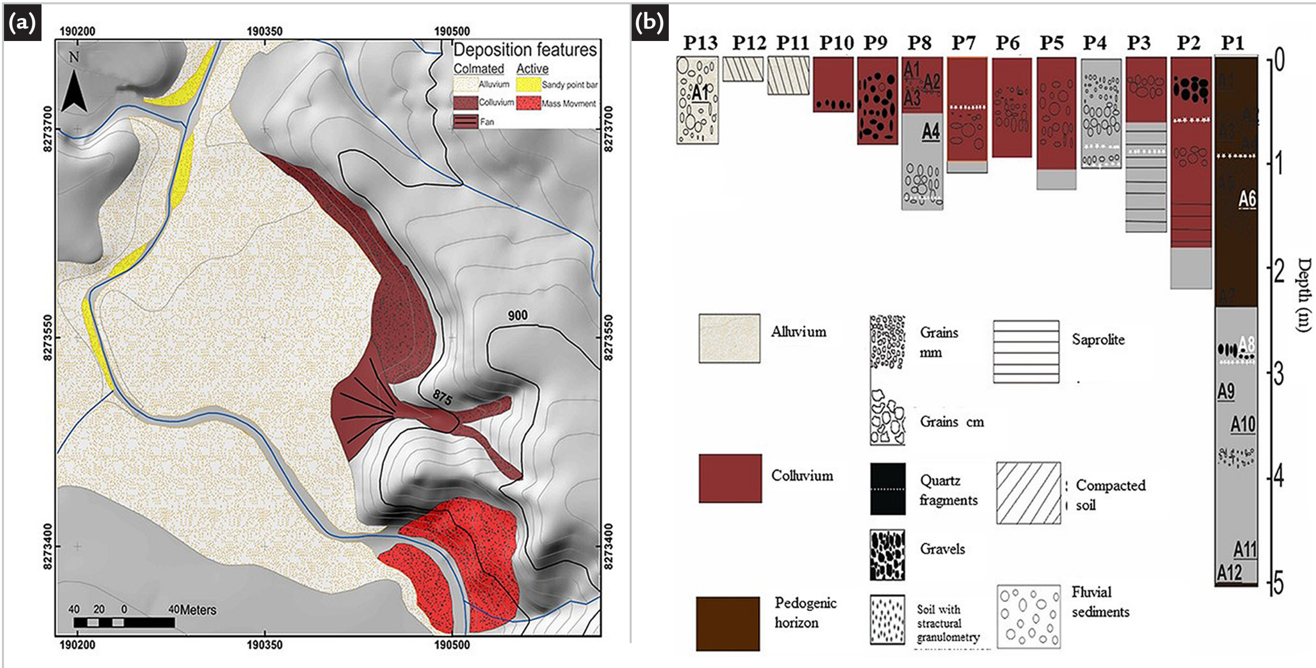

Figure 2 - (a) Geomorphological units of the area, resulted from the soil sampling analysis along with cross-section E1 (Figure 1) showing (i) alluvium; (ii) colluvium; (iii) sandy point bars and (iv) a mass movement and (b) soil analysis results along profile E1. P1-12 are the soil sampling points (adopted from Braga *et al.*, 2018).

2.3 Multi-channel analysis of surface wave (MASW)

The MASW method is based on recording and analyzing the geometric dispersion of Rayleigh surface waves aiming to derive the profile of the shear wave velocity in depth. It is divided into passive and active methods according to the kind of seismic source employed. In this study, the active method was used with data gathered using the same receiver array configuration as applied for shallow seismic refraction and reflection surveying (Park *et al.*, 1999). Active MASW surveys employ impulsive sources capable of providing a broad range of frequencies. Here, the source energy was provided by a hammer weight drop, where higher frequency ranges are produced by lighter sources. The velocity dispersion curves are extracted from the phase delays of the different frequency components of the surface waves recorded by the receiver array (Park *et al.,* 1999). The dispersion curves are inverted in order to obtain the shear wave subsoil model. More details about the MASW can be found in Kanli, (2010).

2.4 Electrical resistivity tomography (ERT)

The ERT method is based on injecting a known amount of current to the ground by two metal electrodes called current electrodes. The amount of current encounters resistance from the subsurface soil conditions (degree of fractures, material types, and degree of saturation) and the potential is developed, which is measured by deployment two other metal electrodes known as potential electrodes. Ohm's law provides a link between the electric current (I), the electrical resistivity of the material, and developed potential difference (ΔV). This relationship is used for the understanding of earth using DC Electrical Resistivity Tomography (ERT). Based on I, ΔV, and electrode array arrangement (K-factor), the apparent resistivity of the ground can be obtained. In the end, these obtained apparent resistivity values are interpreted, and a picture of the subsurface is obtained at an acceptable range of Root Mean Square (RMS) values between observed and calculated resistivity values. Details of the method can be found at Perrone *et al.* (2014) and Rezaei *et al.* (2018). The method is affected by the geometry (K-factor) of the four electrodes on the surface, and hence the technique can be used in different ways (Strelec *et al.*, 2017; Hussain *et al.*, 2017).

2.5 Data acquisition and processing

The survey planning for MASW and ERT was carried out using satellite images. The data were acquired along with three profiles in the study area in orientations such that the projected area can be covered. For the MASW acquisition, used were a 24-channel seismograph (Geode, Geometrics Inc.) along with 14 Hz geophones. The seismic source was provided by a hammer with 8 kg, struck against a metal plate placed on the ground. Energy generation at each point was repeated (5 and 15 times) and then stacked, whereby the signal to noise ratio improved (Akpan *et al.*, 2015). A total of three seismic lines were acquired L1, L2 and L3 with 48 95, and 70 meters in length, respectively. The L2 seismic line, as well as the resistivity ERT-1, line, passes the length of the landslide parallelly. The L3 line, along with ERT-2, runs perpendicularly to cover the landslide, and their small portion touches the landslide scarp at the top (Figure 1). Two profiles covered the landslide, and one covered the alluvial plain (small). The L1 line is taken on alluvial deposits lie behind the landslide, and its end passes through the alluvial, colluvial material interface (with various grain size) presented in previous geotechnical studies (e.g., Braga *et al.*, 2018).

The MASW data (Figure 3) were processed and interpreted with SurfSeis software. The data processing followed three steps; (i) geometry edition (ii) dispersion analysis - generation of the dispersion images (overtones) and extraction of the dispersion curve (iii) inversion of the dispersion curves with the obtention of the 1-D shear-velocity profiles. For the last step, only the inversion of fundamental mode curve was performed. SurfSeis uses the phase-shift method (Park *et al.,* 1999) and for the inversion process, its algorithm is based on Xia *et al.* (1999).

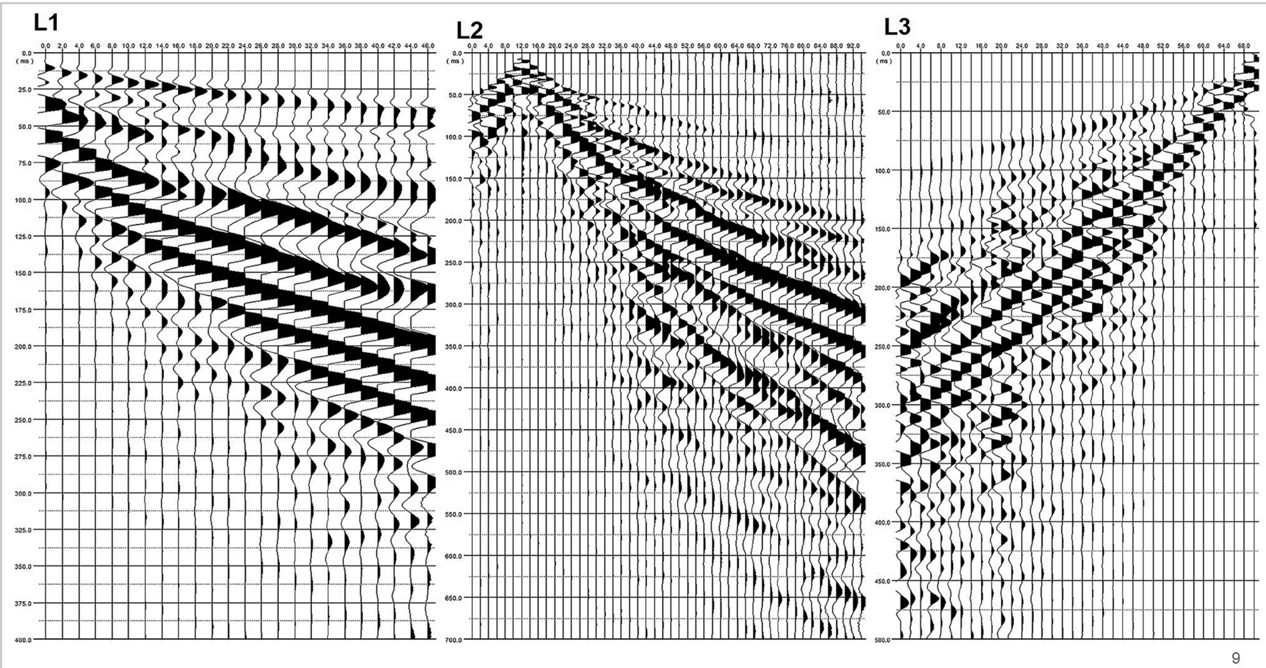

Figure 3 - Unprocessed records at three different MASW lines (L1, L2, and L3).

It had a 5 and 8 m electrode separation of the dipole-dipole (DD) array at parallel (ERT-2), and perpendicular (ERT-1) to the landslide, used were the collection of the DC resistivity data (Figure 1). In order to avoid the possible influences of soil moisture on the resistivity results, the measurements were taken in the dry season. The resistivity measurements along these profiles were made with Syscal-Pro Resistivity meter (IRIS Instruments, France). The acquisition and geometric parameters were registered in a resistivity meter before going to the field, and after that, functioned automatically and took measurements along several electrodes connected with a multicore cable. A DD array of electrodes was used for the acquisition of resistivity data. In DD entire array of electrodes is moved. Array details can be found in Falae *et al.* (2019). The electrode spacing of 5 and 8 m were adopted because DD array sometimes misleads the landslide slip surface estimation, if large electrode spacing (current and potential) is applied (Loke 2004; Rezaei *et al.* 2019). Based on the study objectives, Wenner–Schlumberger and DD arrays are the most common arrays adopted for the landslide studies due to good depth range and the best horizontal resolution (Reynolds, 2011; Pasierb *et al.* 2019). Because the target landslide in the present study is shallow, DD array was adopted for the calculation of the shallow slip surface and permeable path delineation at high spatial resolution. In DD array the current and voltage cables are widely separated, enhancing lateral resolutions at shallow depths and minimizing electromagnetic inductive noise (Pazzi *et al.* 2020) The signal to noise ratio was improved by pouring saltwater at each electrode during acquisition and muting bad data points from the record during the preliminary data scanning step in the Prosys II software. After editing, the data was saved in a new file format compatible with RESIS2DINV of Geotomo Software (Loke, 2004), where the inversion of resistivity data was performed. In this software, a best-fit earth model was generated from the apparent resistivity values. For that cell-based resistivity, the calculation was conducted through the application of smoothness-constrained least-squares inversion method (Sasaki, 1992) that searches for an idealized model for the resistivity distribution in the subsurface and its best-fit with the calculated, measured resistivity values (Colangelo *et al.*, 2008). In this method, the subsurface is divided into rectangular blocks, each representing a single measuring point (Lapenna *et al.*, 2005). The root means square (RMS) error provides the discrepancy between measured and calculated values.

3. Results

The fundamental and first higher modes of Rayleigh waves were observed over the dispersion images of lines L1 and L2. For these two sets of data, we performed the inversion of only the fundamental mode curve as well as the joint inversion of fundamental and first higher modes. However, the results of the former inversion, comparing with other geophysical and geological data and with the fundamental curve inversion, were inconsistent. Furthermore, the inversion of the fundamental mode was sufficient to delimit the interfaces or contrasts of speed that limit the horizons of soft or saturated materials concerning those more rigid, i.e., competent layers. So, only the results of the fundamental dispersion curve inversions were considered in this study. Figure 4 shows the dispersion curves of fundamental (used in the inversion) and first higher modes of Rayleigh wave propagation.

The inversion results are presented in the 1D cross-sections of shear wave velocity (Figure 5). The results demonstrate subsurface layering of the site over a homogeneous half-space. The sections of the three profiles were inverted using the fundamental mode of dispersion curves (Figure 4), based on borehole information (Figure 1).

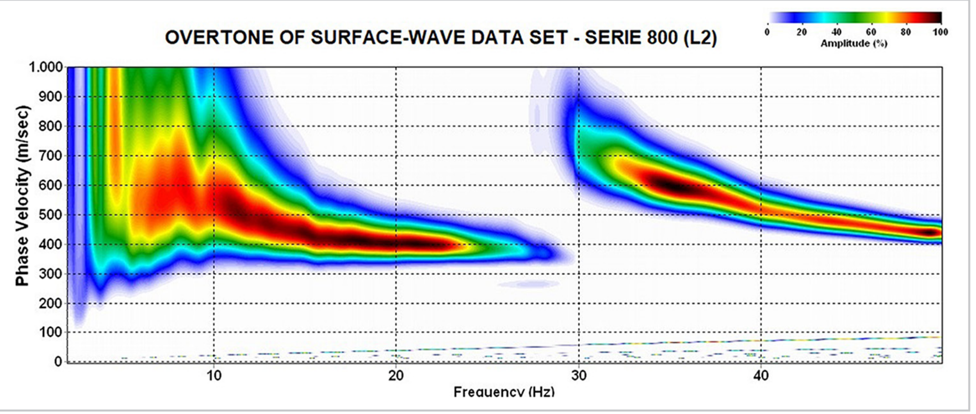

Figure 4 - Velocity spectrum (velocity vs. frequency). The color scale presents the amplitude of the spectral values.

The profile L1 runs over the area of alluvial deposits, where a slight decrease and then increase in Vs with depth is observed, which indicates the absence of any disturbance in the saprolite having varying degrees of compression and moisture contents strata. This increasing trend continued until the investigating depth of 23 m, reaching a maximum value of Vs > 600m/sec (Figure 5). The first decrease in velocity can possibly be related to the presence of the clay layer with a varying degree of moisture up to the depth of 5m (Figure 1). The profile L2, which runs over landslide mass, showed interesting results. The first slight increase in Vs is because of the presence of dry soil while a prominent decrease in Vs (~400 to ~250 m/s) can be seen which starts from ~8 m and ends ~17 m is a clear indication of the presence of disturbed material, which can be related with the landslide mass. From ~18 m depth, the dry and compacted saprolite layer having Vs > 200 m/s started (Figure 5).

The profile L3, which is touching the landslide scarp, showed more significant variations in the shear wave velocity over the landslide, where a decrease in the velocities after 5 m depth (~220 m/s) from the surface is found which indicates a possible presence of the depth of dry soil. It shows stability in Vs values until at a depth of ~8m; after that an increasing trend can be seen. Both of these profiles (L2 and L3) are away from the Contagem River, which indicates the absence of moisture in the subsurface and shows comparatively higher values Vs to the L1 profile. These overall smaller Vs values observed in L1 can be attributed to the proximity to the Contagem River. Another interesting fact can be seen from Figure 5: all profiles showed similarity in increasing trend and Vs values at depth > 20 m which indicates a uniform lithological interface at that depth (saprolite with pebbles).

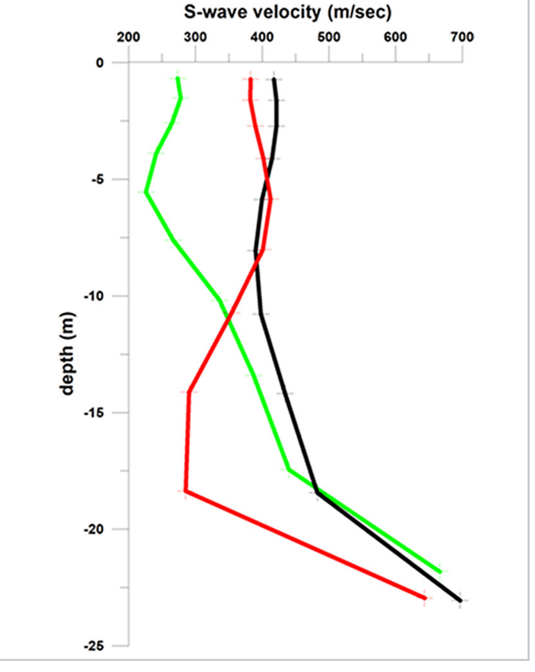

Figure 5 - Results of MASW in the form of 1D shear wave velocity (Vs) cross-sections of the area (L1 (green) L2 (red) and L3 (black). 1D shear wave velocity model (Vs variations with depth).

On the inverted resistivity section ERT-1, the following prominent features are delineated:

(i) Hypothetical landslide boundary, which presented a continuous contrast between conductive and resistive material, was observed. This could be associated with the presence of a sliding surface. The continuous resistive material at the top throughout the extent landslide may be linked with the presence of dry, disturbed, and coarser grain material. The presence of such coarser grain materials is also evident from a previous study on that area (Braga et al., 2018);

(ii) Disturbed materials on top of a valley (the small-scale discontinuities of intermediate resistive materials) are also delineated on the section. This indicates the presence of a fluvial valley as described by Braga *et al.* (2018);

(iii) Compacted clayey material shows intermediate values of resistivity throughout the entire length of the profile; however, its thickness and resistivity value decreased as moving away from the landslide body towards a small seasonal stream that lies at the end of the profile (Figure 6). From these resistivity values, the area might consist of relatively coarse-grained material, which may provide some pathways for the rainfall infiltrating water that comes through the stream. This can potentially allow pore water pressure to build up in the landslide mass, triggering the landslide's reactivation in the case of some future extreme rainfall events. This has been highlighted as a possible mechanism for the reactivation of rainfall triggered shallow landslides in the region (Ehrlich *et al.*, 2018);

(iv) A possible permeable path through which water infiltrates in the proximity of a small seasonal stream. At the beginning of the profile (away from landslide), a low resistivity zone appeared (Figure 6), which could be linked with the presence of fine-grain material having a plentiful amount water, which is provided by the stream. However, the lateral extent and depth limit is not possible to analyze because of the shorter length of the ERT data acquisition profile;

(v) At the bottom, high resistivity values appeared that might be related to the presence of a Saprolite layer. However, it showed different values of resistivity that might be related to the variable degree of compaction, moisture, and weathering. These findings are consistent with the borehole information for a nearby area (Figure 1).

On the profile (ERT-2) that runs parallel to landslide, different features are observed on the inverted resistivity cross-section at greater depth (Figure 7). In particular, the black dotted line shows four different features. Firstly, a hypothetical landslide boundary is found at ERT-2. This is similar to profile ERT-1; however, its length is larger than the one bereaved at ERT-1. Secondly, along the shallow slip surface, another layer of compacted and dry landslide material is found, which might be labeled as a previous landslide slip surface. In most cases, due to the presence of water, as well as the materials' disturbance in the slipped soils, the electrical resistivity of soil layers can be considerably low. However, this was not observed in the current study because the measurements were taken in the dry season, where the soil was mostly dry at shallow depths. A similar phenomenon has been reported by Pasierb *et al.* (2019). Thirdly, a continuous low resistivity material was also found, which might be related to a possible permeable path through the water, whose water from the Contagem river percolates into the landslide mass where it can also build pore water pressure, which can be a possible trigger for its reactivation. Fourthly, Saprolite with varying degrees of weathering and moisture contents was also found in ERT-1 (Figure 6).

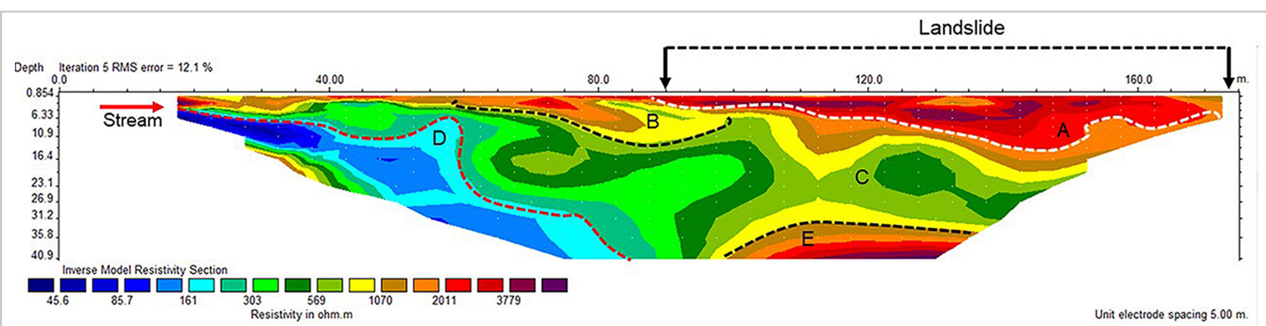

Figure 6 - Modeled resistivity tomograph of profile ERT-1 that was taken transverse to the Sobradinho landslide. The dotted lines show different features such as (A) hypothetical landslide boundary, (B) disturbed material on the top of a valley, (C) compacted clayey, and (D) a possible permeable path through which water can infiltrate because of proximity to a small seasonal stream. Color scale represents the values of resistivity in ohm.m.

The value of RMS error above 5 is in a typical pattern for such type of study, and its processing is adequate. RMS error is a parameter that quantifies the variation or deviation around the average of the input data, and data acquired in this study has a wide range of resistivity variations. These variations may be related to the presence of dry soil and aquifer level in the profile. Some of the previous studies on landslides with a high value of RMS justify the consistency of our data (e.g. Crawford and Bryson, 2018; Supper *et al.* 2008). According to Sass *et al.* (2008), the contact problems between the cables and single electrodes probably led to noisier data and a higher RMS error (above 5%) but did not gravely affect the data interpretation.

The findings of the present study show that ERT is a very suitable technique for the site characterization (delineation of slip surface and the permeable paths) of a complex landslide over tough terrain. The surface wave-based analysis, namely, MASW, did not prove very effective in the estimation of the slip surface of Sobradinho landslide. MASW completely fails in the delineation of permeable path and landslide slip surface; however, the surface stratification developed with this method requires further validation measures in the future.

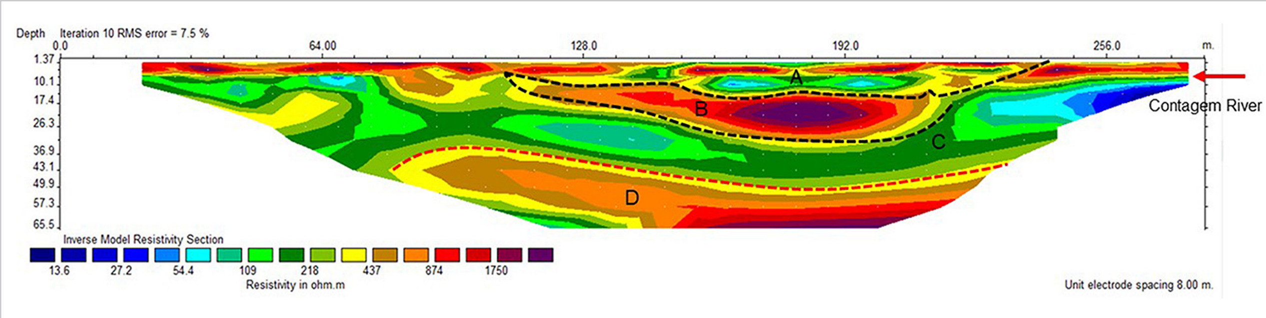

Figure 7 - Modeled resistivity tomograph of profile ERT-2 that was taken parallel to the Sobradinho landslide. The black dotted line shows the different features: (A) hypothetical landslide boundary, (B) compacted and dry landslide material might be labeled with previous landslide slip surface, (C) a continuous low resistivity material might be related with a possible permeable path through the water, whose water from the Contagem river percolates and (D) Saprolite with varying degree of weathered and moisture. Color scale represents values of resistivity in ohm.m.

In this study, MASW only gave 1D Vs model of the subsurface, which is a disadvantage, unlike the ERT method that provided a 2D model of the subsurface. Such 2D models provide lateral as well as vertical variations, which are highly important for landslide studies. ERT results provided more details, while MASW results were not so clear and practical. The subsurface groundwater flow paths (delineated on resistivity tomographs) were not identifiable on the 1D cross-sections obtained from MASW. In terms of 1D variations with depth, the results from L2 that were taken at the landslide, showed a slip surface, which is also delineated on the ERT results. In short, MASW can provide information about the depth of slip surface, while ERT is good for the estimation of slip surface depth as well as the permeable paths that lead to build up pore-water pressure in the landslide mass, which may cause landslide reactivation in extreme rainfall conditions.

4. Conclusions and discussion

A geophysical investigation combining MASW and ERT methods was carried out in this study to examine if such combination could improve the characterization and delineation of the slip surface of the Sobradinho landslide located in a morphologically active fluvial valley (the Federal District of Brazil). The following conclusions can be drawn from the study.

A bimodal propagation of the Rayleigh wave was observed over the dispersions obtained from all three seismic lines taken in the study. The MASW results of line L1 showed an increasing trend of VS, indicating the increase in layer stiffness related to the densification of strata with depth. However, relatively low values of Vs are observed within close proximity to the Contagem River, which may indicate the presence of moisture in the strata. The landslide slip surface was found at about 8 m depth on the resistivity profiles. However, on the seismic line that touched the landslide showed an anomalous decrease in Vs over the landslide at a depth range of ~8-17 m, which may be attributed to the presence of the landslide body. The low signal to noise ratio of the seismic record at some of MASW results made the interpretation dubious.

Moreover, it may be concluded from the results of the present study that ERT method in comparison with the MASW method appears to be more potent for imaging the geometric boundaries of complex roto-translational landslides, including fast data acquisition at low costs and quick data processing. For future study, the techniques could be applied to monitor landslide bodies continuously for the time-lapse variations in resistivity and surface wave properties.

The study indicated there were some discontinuities filled with high-resistivity materials over the horizontal and transverse directions of landslide body that might be linked to rainfall infiltration and a source of pore water pressure. Therefore, these may lead to the reactivation of a landslide at the slip surface in the case of extreme rainfall events. As such, future detailed studies are recommended for the confirmation of the aforementioned results.

Acknowledgment

The authors acknowledge the support of the following agencies: the National Council for Scientific and Technological Development (CNPq), the Support Research of the Federal District Foundation (FAP-DF), the University of Brasilia and, the Pool of Brazilian Equipments (PegBr), Rio de Janeiro. First author would like to thank Dr. Marcelo Rocha of UnB for providing Geophones used in MASW data acquisition.

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Received: 26 July 2019 - Accepted: 31 May 2020.