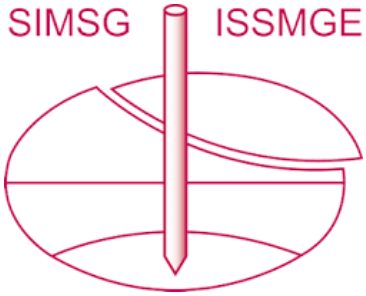
INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING




*This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:*

*https://www.issmge.org/publications/online-library*

*This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.*

*The paper was published in the proceedings of the 6th International Conference on Geotechnical and Geophysical Site Characterization and was edited by Tamás Huszák, András Mahler and Edina Koch. The conference was originally scheduled to be held in Budapest, Hungary in 2020, but due to the COVID-19 pandemic, it was held online from September 26th to September 29th 2021.*

# Inversion of Electrical Resistivity Tomography (ERT) and Time Domain Electromagnetic (TDEM) data for geotechnical site characterization of PLLN alluvial area, Lisbon.

Pedro Baltazar-Soares
*Instituto Dom Luiz (IDL), Faculdade de Ciências, Universidade de Lisboa, Campo Grande, 1749–016, Lisboa, Portugal, pabsoares@fc.ul.pt*

Jeniffer Costa Barreto Viegas
*Università di Cagliari, Department of Civil and Environmental Engineering and Architecture, Cagliari, Italy, jc.barreto@unica.it*

Giulio Vignoli
*Universitá di Cagliari, Department of Civil and Environmental Engineering and Architecture, Cagliari, Italy & Geological Survey of Denmark and Greenland, Department of Groundwater and Quaternary Geology Mapping, Aarhus, Denmark,*
*gvignoli@unica.it*

Claudia Escada[1], Fernando Monteiro Santos[2], Francisco Martinez-Moreno[3]
*Instituto Dom Luiz (IDL), Faculdade de Ciências, Universidade de Lisboa, Campo Grande, 1749–016, Lisboa, Portugal*
*claudia.escada@gmail.com[1], fasantos@fc.ul.pt[2], fjmoreno@fc.ul.pt[3]*

Jaime Santos
*Instituto Superior Tecnico, Department of Civil Engineering, Architecture and Georesources, Lisbon, Portugal*
*jaime.santos@tecnico.ulisboa.pt*

**ABSTRACT:** Geophysical methods are cost-effective tools to characterize large areas when compared with conventional ground surveys like, e.g., boreholes, CPT, DMT. The capacity to reach deeper depths with the reliable resolution has been one of the advantages of applying geophysical methods for geotechnical site characterization. This paper presents a case of study in which electrical resistivity (ERT) and time-domain electromagnetic (TDEM) surveys were carried out in the Northern Lisbon Logistic Park (PLLN), located in Castanheira do Ribatejo – Lisbon, for the construction of industrial warehouses. The study area is in a flood plain, in Tagus River's alluvial deposits with a maximum thickness of about 20 to 30m. In previous studies, the site was already characterized via seismic surveys, boreholes, SPT, and other tests. The goal of this study is to confirm and compare the new outcomes against the results obtained previously, in order to better identify the geological layers and improve the resolution of the reconstructions at depth.

**Keywords:** TDEM; ERT; site characterization; inversion

## 1. Introduction

Geophysical methods originally developed for mining and geothermal purposes are nowadays widely applied to environment and engineers investigations. The ERT and TDEM methods have been applied to the exploration and monitoring of natural resources, as well as in the mapping of groundwater and contaminated areas [1,2,3,4].

In Denmark, a national groundwater mapping project has been using massively geophysical methods (especially TDEM) to detect and characterize water reservoirs and guarantee their optimal protection and management. Similar initiatives have been also implemented in countries such as India and Thailand [5]. In Canada, TDEM data have been utilized to construct electrical resistivity sections for the groundwater assessment of aquifer formations in glacial and coastal deposits [6]. In Norway, an extensive geophysical, geomorphological and geotechnical survey was carried out, including an electrical resistivity tomography (ERT). This ERT was conducted after a quick-clay landslide, enabling the identification of possible areas at risk. [7]. Nobes et al.[8] have applied near-surface geophysical methods such as electromagnetic (EM-31), electrical resistivity sounding, ground penetrating radar and total magnetic field and magnetic gradient measurements to explore liquefaction features occurred after the earthquake on February 22, 2011, in Canterbury – New Zealand.

Among the different geophysical methods, ERT and TDEM have been largely applied to site characterization since they are not only financially attractive, easy to carry out and time-saving but also have a great potential in terms of accuracy and precision in the reconstruction of the subsurface [9, 10, 11]. In fact, the potential of those methods in geological structures characterization, stratigraphy profiling, as well as in improving the conditions associated with the drilling process should be good reasons for their popularity. These aspects are particularly important since the major part of the costs are associated with drilling and core sampling, usually performed without prior geophysical investigations.

The objective of this work is to show how ERT and TDEM methods can be used to improve and complement geological and geotechnical information.

## 2. Study Area

The study area is located in the Northern Lisbon Logistic Park (PLLN), in Castanheira do Ribatejo (Vila Franca de Xira, Portugal), Fig. 1.

On the left bank of the Tagus River, the area has good access to road and maritime infrastructures; this makes it very interesting for future construction developments. In the study area, several geotechnical surveys have been performed because of future construction activities. The results of those geotechnical surveys are published in Lopes *et al*. [12]. Two seismic methods (The active Multichannel Acquisition of Surface Waves -MASW method and the passive Horizontal to Vertical Spectral Ratio - HVSR) were applied in Lopes *et al.* [12] and the results, jointly inverted identifying 3 layers and the bedrock. The first and more superficial layer is a fill deposit with 2 m, the second is a compressible alluvium soft soil layer with 18 m, and the third layer is composed of two materials – fine sand and colluvium deposits with about 18 m.

According to the geological map [13], the present geology consists mainly of alluvium with clay content :

- Alluviums (Holocene), reaching a thickness of the order of 60 m. It is a fluvial-marine complex, consisting mainly of brown or dark gray sludge, sandy sludge, gray sands, alternations of sandy sludge and muddy sands, as well as muddy sands with gravel at the base:

- Deposits of river terraces (Plio-Pleistocene). They are mainly made of clays and conglomerates, clay sands and black clays; at the top, at least locally, there are conglomerates with limestone;
- Some kilometers towards the north, formations of Pliocene (Ulme Formation), Miocene (Alcoentre Formation) and Paleogene (Benfica Formation) occur. On the west side, the study area consists of limestones and pelites.

The geology has been confirmed by several prospecting studies [12] detecting the different alluvial layers. Thus, from the:

- Landfills, between 1.5 and 3.4 m thick. Consisting of sandy clays, sometimes with varying values of nature and size.
- Alluvial sediments, divided into four types from top to bottom: silt, silt sludge, silt clay, sandy gravel at the base. The thickness is approximately 46 m, including 8 to 10 m of corresponding gravel thickness.

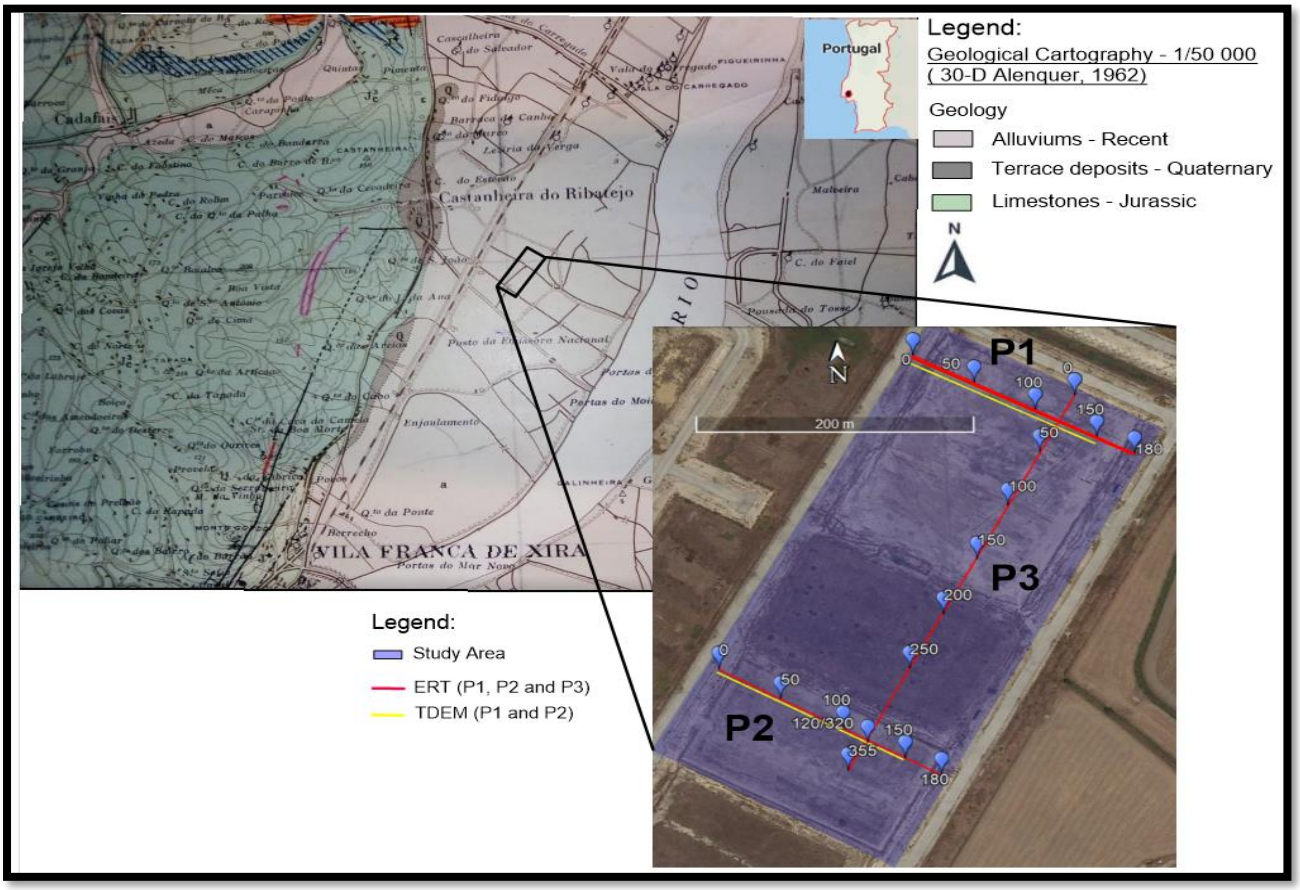



**Figure 1.** Location of the geophysical profiles inside the study area (below) and geological sketch (above). Red line – Electric Resistivity Tomography (ERT); yellow line – Time-Domain Electromagnetic (TDEM).

• Sandy clays and sparse conglomerate silt clay stones from Miocene, ≈ 46 m in depth. Its thickness is between 3-6 m, according to the information from the drilling performed on the area.

## 3. Methodology

This paper presents the results obtained by inverting the recently collected ERT and TDEM data.

In the TDEM method, a varying electrical current is flowing through a cable generating a primary magnetic field. When the current it's cut off, variations of the primary field lead to eddy currents diffusing in the subsurface. The intensity of these currents depends on the electrical properties of the ground (mainly the electrical resistivity distribution). In turn, the propagation of the eddy currents generates a secondary magnetic field that can be recorded by the receiver(s) of the TDEM instrument [14].

In ERT, four electrodes are used conventionally: an electric direct current is injected through two current electrodes (A, B) while the generated potential differences are measured at two potential electrodes (M, N). From the current injected and the observed voltage, the apparent resistivity can be calculated and then inverted to retrieve the correct resistivity distribution of the subsurfaces.

The TDEM data acquisition was made with the equipment TEM-FAST 48 HPC, which is a portable equipment developed by AEMR Ltd. Company.

Three profiles were carried out. Two of them with loops of 25 m, 10 m spaced over a profile of 150 m (so, 15 soundings per profile and a total of 30 soundings). The third one was carried out with a 50 m x 50 m loop consisting of 20 m spaced soundings over a 150 m profiles (7 soundings in total). All profiles were in NW-SE direction, (Fig. 1, yellow line).

The ERT data acquisition was made using the Syscal Pro Switch resistivity-meter, built by IRIS Instruments. It comprises 4 cables with 18 takeouts, given rise a total of 72 outputs where electrodes are connected. The electrode spacing along the profiles was 5 m, using a Wenner-Schlumberger configuration, which confers a better vertical and laterally resolution.

The profiles length was 180 m for two of them (NW-SE, 36 electrodes) and 355 m (NE-SW, 72 electrodes) for the third one. These differences in length are proposed in order to influence the maximum depth of investigation, (Fig. 1, red line).

### 3.1. TDEM Inversion

TDEM data processing and inversion were performed using the TEM-RESEARCHER software.

The initial model was defined with 3-4 layers, (Fig. 2) depending on the data of each sounding. The number of layers was increased in case of too high final data misfit.

The TDEM inversion process is carried out, adjusting layer thickness and resistivity values, automatically until the minimum of the data misfit is reached.

In the present work, the resulting resistivity models were selected when the data misfit was between 1 and 4%. The forward and the inverse models are presented in Fig. 2 for one specific sounding.

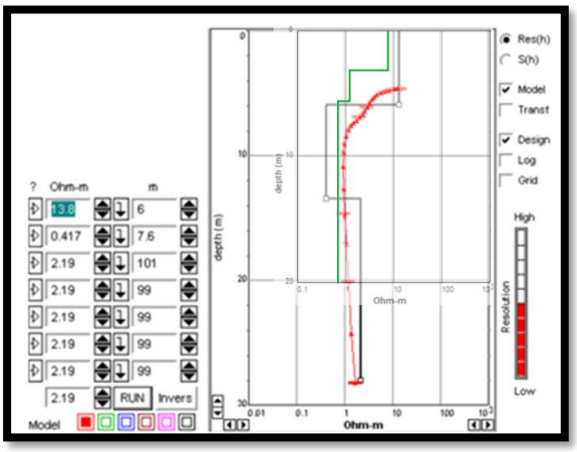



**Figure 2.** Example of one TDEM sounding in TEM-RES – Red line – apparent resistivities (ohm.m) in function of depth (m); black line – forward model; green line – inversion model.

### 3.2. ERT Inversion

For the processing of the ERT data, the program used was RES2DINV [15]. For the initial model, the following parameters were selected: i) for the horizontal mesh, the one providing the best result was a 4 node mesh due to the high resistivity contrasts; ii) for the forward modeling, the type of method adopted was the finite-difference method. The same parameters were kept constant for all ERT profiles.

RES2DINV [15] is a program that generally uses the least-square inversion to fit the data. This means that the algorithm minimizes the L2-norm of the difference between the measured and the calculated apparent resistivities. However, when measurements contain 'outliers', it might be useful to use an L1-norm approach, instead. So, to reduce the effects of particularly noisy data, in the present study, the L1-norm strategy (robust constrain) has been used (Fig. 3).

## 4. Results

### 4.1. Profile 1

This profile was acquired over an alluvial zone with the uppermost part filled with landfill deposits. In both profiles (TDEM, and ERT), three layers with relatively high resistivity contrasts are evident.

The results of this profile are shown in Fig. 4 and described below;

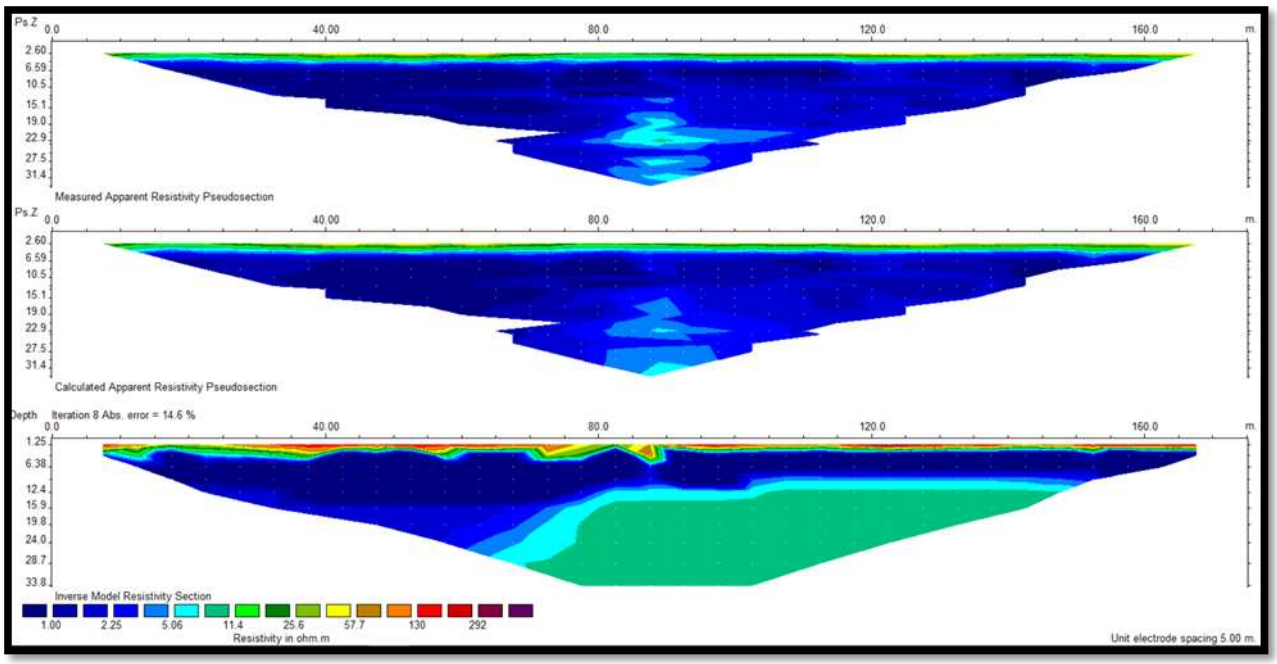



**Figure 3.** Example of the Profile 2 inversion – From top to bottom; pseudo section of measured apparent resistivities; pseudo section of calculated apparent resistivities and inverted resistivity distribution. Use of the L1 norm approach to reduce the effects of noisy data.

• The shallowest layer (L1), about 5 m thick, has high resistivity (100-300 ohm.m in ERT), corresponding to the mentioned landfill deposits. In the TDEM reconstruction, the low resistivity value in the first meters is due to the (well-known) relatively poor shallow resolution of this method (caused by the relatively late time-gates in combination with the size of the loop). Despite that, the TDEM resistivity section reproduces well the overall behavior of the resistivity with depth. In particular:

• From 5 m downwards, a layer of about 15-17 m thick with low resistivity (1-3 ohm.m) extends over the entire profile, being in good agreement with the ERT result. This layer is consistent with the presence of clays, due to its particular effect on measurement results, decreasing the resistivity.

• At the bottom of the profile appears a more resistive layer compared to the previous one, with values of 20-30 ohm.m. This layer is well defined in TDEM and, again, its presence is confirmed also by the ERT. This resistive layer could indicate the top of the bedrock (approximately 30 m).

## 4.2. Profile 2

This profile was measured 300 m south of P1, with the same direction and lengths (Fig. 1). As in P1, the horizontal arrangement of the material is clearly visible; the section consists of three well-defined layers as detected by both the ERT and TDEM results.

The results of this profile are showed in Fig. 5 and discussed below:

• The shallower layer of 5 m thick has a resistivity of 25-50 ohm.m that extends throughout the section. Not surprisingly, as in the previous profile, the TDEM profile does not recover the resistivity at the first meters.

• From 5 m depth, the resistivity drops to values in the order of 1 ohm.m (L2). This layer has an irregular thickness between 0 and 80 m over the ERT profile; then its thickness reduces down to 10-15 m. This layer is well retrieved by the TDEM, with resistivity values similar to those in the ERT model (1 ohm.m). The discrepancy between the ERT and TDEM results regarding the left portion of the section can be easily explained in terms of the footprint of the TDEM measurements at around 20 m depth. In fact, the physics of this methodology allows a limited lateral resolution (especially at depth).

• At the bottom of the profiles, a more resistive layer (L3) appears, with resistivities ranging from 10-30 ohm.m. A gradual increase of resistivity values from 80 m (at 20 m depth) is observed, consistently with the ERT results. Hence, it worth noting that, despite the limited lateral resolution, TDEM can, at least, infer the presence of a lateral variation.

This section reaches a depth of approximately 30 m.

## 4.3. Profile 3

The last profile reaches greater depths and it has a different orientation (see Fig. 1). It was performed perpendicular to P1 and P2 (see Fig. 6), crossing them at 130 m (**P1** - 38°59'20.60"N, 8°57'33.10"W; **P2** - 38°59'11.61"N, 8°57'39.33"W).

It has the same superficial structure and resistivity values than the previous profiles, achieving a depth of investigation of 68 m and an overall length of 355 m.

The results of this profile are shown in Fig. 6 and described below:

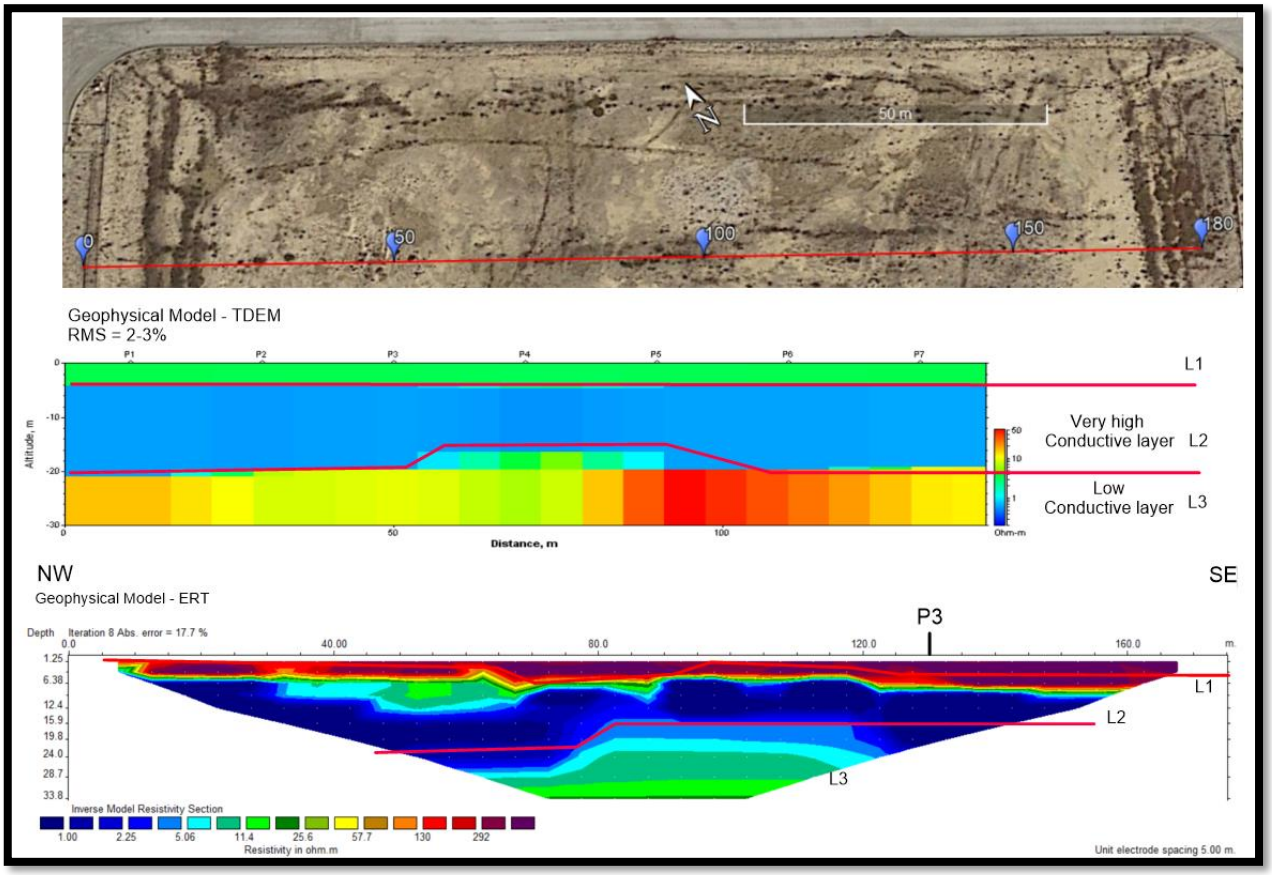



**Figure 4.** Results from Profile 1. Location sketch (top), TDEM (middle) and ERT (bottom). Red line – Layers (L1, L2 and L3). TDEM results shows high resistivities (in red) correlated with the appearance of L3 in ERT.

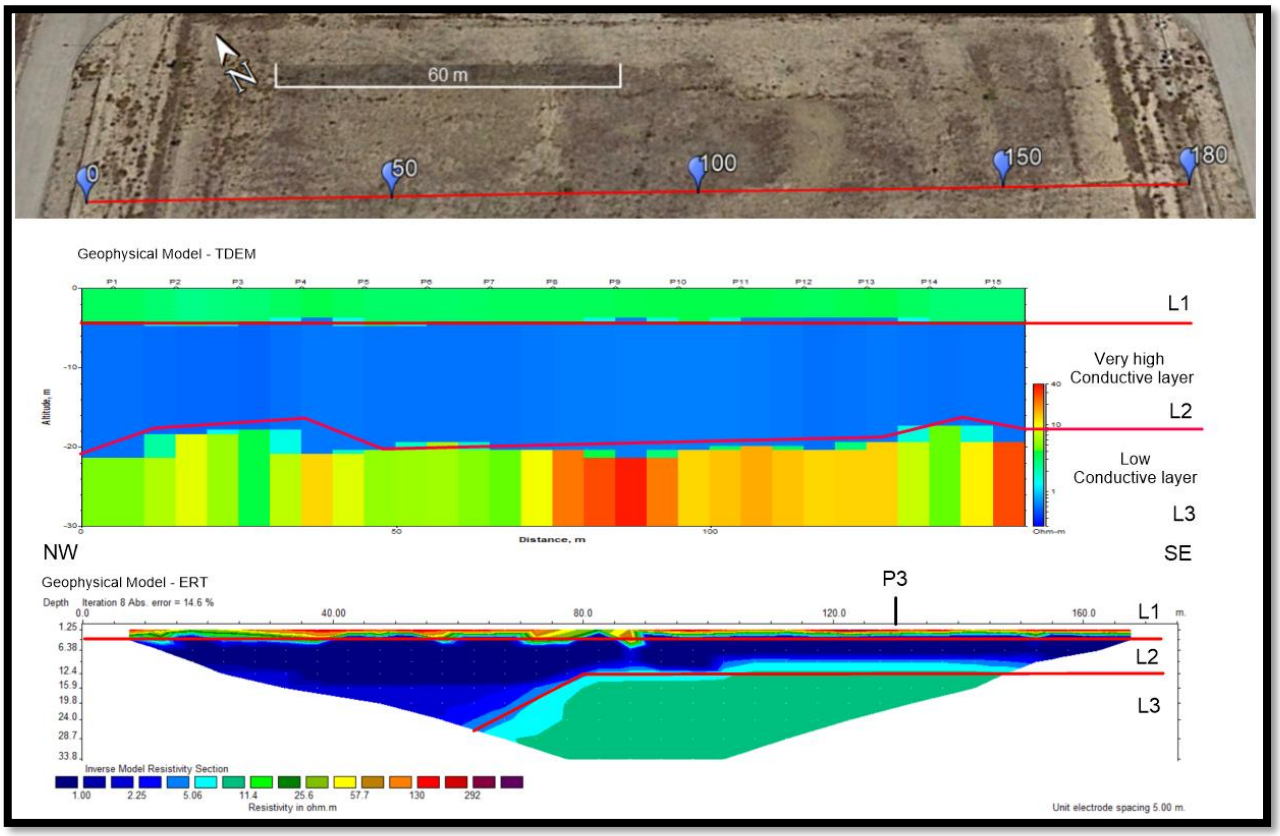



**Figure 5.** Results from Profile 2. Location sketch (top), TDEM (middle) and ERT (bottom). Red line – Layers (L1, L2 and L3). The increasing resistivity values in TDEM, mainly form 70 m until the end, are correlated with the appearance of L3 in ERT profile.

• It has a first layer of approximately 5 m thick up to 195 m over the profile, and, after that, it significantly increases its thickness up to 15 m. This more resistive surface layer, highlighted in all profiles, may have an anthropic origin as mentioned above.

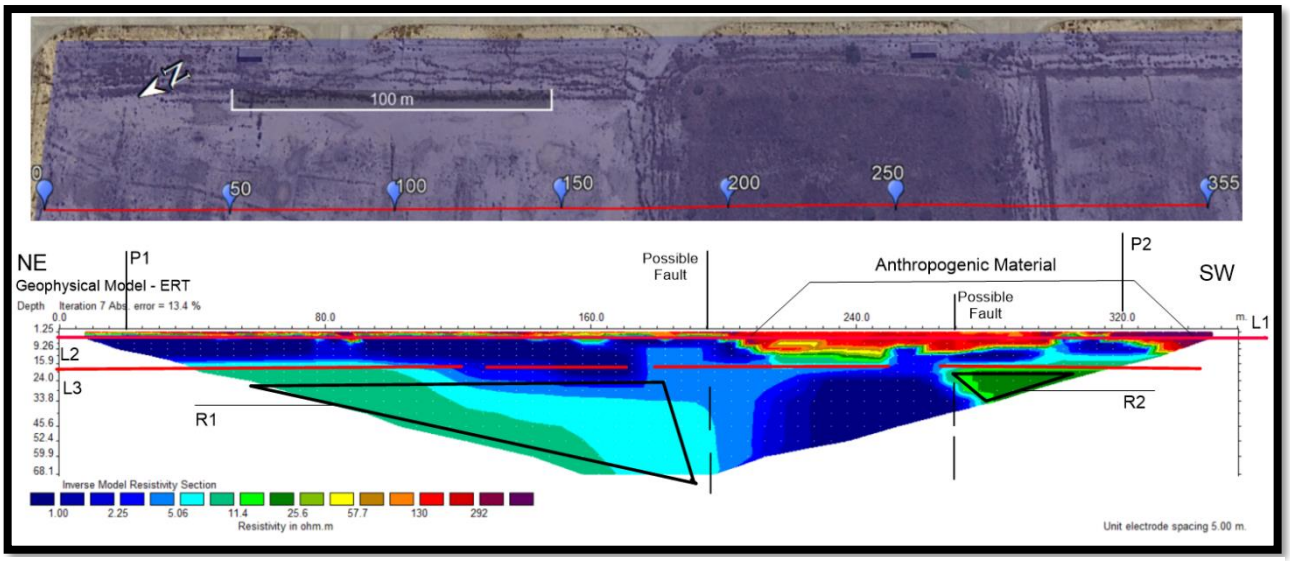



**Figure 6.** Results from Profile 3, with identification of possible faults. Green lines - profile 1 and 2 intersections. The R1 and R2 are resistive layers that could represent the bedrock.

- Similar to the other profiles, from 5 m downwards, a layer with very low resistivity values (L2), 1 ohm.m, has a constant thickness up to 195 m. These values may indicate the presence of clay.
- Below, there are more resistive volumes (indicated as R1 and R2 in Fig. 6) with values of 10-30 ohm.m and also present in the other profiles (L3). Embedded in this layer, between 195-270 m, there is a very low resistivity anomaly of 1 ohm.m corresponding to the presence of clay, as in the L2. So, the resistive R1 and R2 may be the bedrock, whereas the conductive area in the middle could correspond to the weathered bedrock.

This result allows the identifications of zones of possible bedrock, as well as possible volumes of clay material. Terrains that are rich in clay are usually characterized by poor geomechanical properties and might be affected by subsidence when compressed.

## 5. Discussion

The main objective of this research was to test the effectiveness of electrical and electromagnetic methods in discriminating between bedrock and areas possibly affected by subsidence.

The results were satisfactory. The applied techniques allowed the reconstruction of the bedrock surface, as well as the detection of zones with high clay content – corresponding to areas with lower mechanical robustness likely to subsidence under high compression.

- Its thickness is irregular over the profile, however, the 5 m thickness of the first layer associated with the anthropogenic material is clearly visible. The low resistivity values (1-5 ohm.m) in the second layer are compatible with the presence of clay (so with poorer geomechanical properties).
- The ERT could not always reach the bedrock. However, the ERT results are confirmed by the TDEM profiles and together indicate a general depth of the bedrock at around 25-30 m.

Regarding the model results, for a good model fit the average misfit must be lower than 5%. In the present work, the % of misfit was between 1-4%., which creates a reliable model for interpretation. The ERT root mean square percentage (RMS%) was a little higher, reaching in some of the profiles at 17%, this might be because of the higher resistivity contrasts in the first meters of the subsurface, making the root of the mean or average of the all data increase. The principal factor of this high resistivity values compared with the values of the profile in depth is the presence of anthropogenic material, leading to a contact resistances in order of 10 Kohm.m.

## 6. Conclusions

Although the results had been satisfactory, there is still room for improvement. The introduction of geotechnical logs to confirm the results obtained by geophysical methods is crucial to understand and get a better interpretation of the model In that context, an improvement of this work will be developed in the near future and will be the base of further works.

The unambiguous ability to characterize sub-surface structures makes ERT and TDEM methods powerful tools to investigate areas characterized by possible subsidence and to detect the bedrock top surface.

Geophysical methods are cost-effective when used over large areas, and when compared with conventional ground investigation methods like boreholes, CPT, DMT among others, as well as the capacity of reaching deeper depths.

These methods, together with laboratory analyzes and other types of direct methods, can play a fundamental role in better understanding and interpreting the ground sections.

## Acknowledgment

The authors want to acknowledge MERLIN Properties for authorizing the publication of this paper.

## References

[1] McNeill, J. D. "7. Use of Electromagnetic Methods for Groundwater Studies," Investigations in Geophysics:pp.191-218, 1990. https://doi.org/10.1190/1.9781560802785.ch7

[2] Benson, A. K. "Applications of ground penetrating radar in assessing some geological hazards: examples of groundwater contamination, faults, cavities". Journal of Applied Geophysics, 33(1-3), pp.177-193, 1995.https://doi.org/10.1016/0926-9851(95)90040-3

[3] Mota, R., Santos, F. M., Mateus, A., Marques, F. O., Gonçalves, M. A., Figueiras, J., & Amaral, H. "Granite fracturing and incipient pollution beneath a recent landfill facility as detected by geoelectrical surveys". Journal of Applied Geophysics, 57(1), pp. 11-22, 2004.https://doi.org/10.1016/j.jappgeo.2004.08.007

[4] Gonçalves, R., Farzamian, M., Santos, F. A. M., Represas, P., Gomes, A. M., de Pina, A. L., & Almeida, E. P. "Application of time-domain electromagnetic method in investigating saltwater intrusion of Santiago Island (Cape Verde)". Pure and Applied Geophysics, 174(11), pp.4171-4182, 2017.https://doi.org/10.1007/s00024-017-1642-7

[5] Klee, P. "Greater water security with groundwater". Groundwater mapping and sustainable groundwater management. In: The Rethink Water Network and Danish Water Forum white papers, Copenhagen. Disponibilesu www. rethinkwater. dk. 2013.

[6] Simard, P. T., Chesnaux, R., Rouleau, A., Daigneault, R., Cousineau, P. A., Roy, D. W., ... & Poignant-Molina, L. "Imaging Quaternary glacial deposits and basement topography using the transient electromagnetic method for modeling aquifer environments". Journal of Applied Geophysics, 119, pp. 36-50, 2015.https://doi.org/10.1016/j.jappgeo.2015.05.006

[7] Solberg, I. L., Long, M., Baranwal, V. C., Gylland, A. S., &Rønning, J. S. "Geophysical and geotechnical studies of geology and sediment properties at a quick-clay landslide site at Esp, Trondheim, Norway". Engineering Geology, 208, pp. 214-230, 2016.https://doi.org/10.1016/j.enggeo.2016.04.031

[8] Nobes, D. C., Bastin, S., Charlton, G., Cook, R., Gallagher, M., Graham, H., ... & Templeton, S. "Geophysical imaging of subsurface earthquake-induced liquefaction features at Christchurch Boys High School, Christchurch, New Zealand". Journal of Environmental and Engineering Geophysics, 18(4), pp. 255-267, 2013.https://doi.org/10.2113/JEEG18.4.255

[9] Vignoli, G., Fiandaca, G., Christiansen, A.V., Kirkegaard, C. and Auken, E., 2015. “Sharp spatially constrained inversion with applications to transient electromagnetic data”. Geophysical Prospecting, 63(1), pp.243-255.

[10] Fiandaca, G., Doetsch, J., Vignoli, G. and Auken, E., 2015. “Generalized focusing of time-lapse changes with applications to direct current and time-domain induced polarization inversions”. Geophysical Journal International, 203(2), pp.1101-1112.

[11] Mastrocicco, M., Vignoli, G., Colombani, N. and Zeid, N.A., 2010. “Surface electrical resistivity tomography and hydrogeological characterization to constrain groundwater flow modeling in an agricultural field site near Ferrara (Italy)”. Environmental Earth Sciences, 61(2), pp.311-322.

[12] Lopes, I., Tavares, G., Ferreira, G., Peniche, B., & Santos, J. "Joint Inversion of MASW and Rayleigh Wave Ellipticity in the Site Characterization of PLLN Alluvial Area, VFX, N Lisbon". In 24th European Meeting of Environmental and Engineering Geophysics. Porto, Portugal. Sep/09/2018.10.3997/2214-4609.201802591

[13] Zbyszewski, G., da Veiga Ferreira, O., & de Assunção, C. T. " Carta geológica de Portugal na escala 1: 50 000: notícia explicativa da folha de Ilha de Santa Maria (Açores) ".1965. (English translation) Geological chart of Portugal in the scale 1: 50 000: explanatory news of the leaf of Santa Maria Island (Azores). 1965.

[14] Auken, E., Christiansen, A.V., Kirkegaard, C., Fiandaca, G., Schamper, C., Behroozmand, A.A., Binley, A., Nielsen, E., Effersø, F., Christensen, N.B., Sørensen, K., Foged, N., and Vignoli, G., 2015. “An overview of a highly versatile forward and stable inverse algorithm for airborne, ground-based and borehole electromagnetic and electric data. Exploration Geophysics, 46(3), pp.223-235.

[15] Loke, M. H. (2012). 2-D and 3-D electrical imaging surveys. Geotomo Software Sdn. Bhd., Gelugor, Penang, Malaysia.