Brazilian Journal of Geophysics
BrJG
Brazilian Journal of Geophysics 40 (2022), Suppl. 1, 1–15
Brazilian Geophysical Society
ISSN 2764-8044
DOI: 10.22564/brjg.v40i5.2149

DETERMINATION OF WATER TABLE DEPTH USING GEOPHYSICAL METHODS

Otavio Coaracy Brasil Gandolfo

[1] Instituto de Pesquisas Tecnológicas de São Paulo - IPT, SP, Brazil

*Corresponding author email: gandolfo@ipt.br

ABSTRACT. Water table (WT) depth is an important parameter in engineering and environmental studies. This information can be easily obtained through drilling boreholes. Some geophysical methods can also contribute to indirectly determine the WT depth. The methods that are effective in achieving this goal are GPR (ground penetrating radar) and electrical resistivity (ER). Other methods, such as FDEM (frequency domain electromagnetic method), seismic refraction, and seismic reflection, can also be employed to measure WT depth. This article presents a discussion on the use of some geophysical methods to determine WT depth, based on a brief literature review and analysis of data obtained by the author.

Keywords: water table; geophysical methods; GPR; electrical resistivity; seismic methods.

INTRODUCTION

Knowledge of water table (WT) depth (the boundary between unsaturated soil and saturated soil) is an important parameter in many hydrogeological and engineering surveys.

Geophysical methods, which are indirect survey techniques, can provide qualitative and quantitative information on WT depth prior to drilling boreholes or when this information is not readily available at the site under investigation.

A broad application of the geophysical methods to groundwater investigation is presented by Kirsch (2006), showing some examples for the specific case of the determination of the depth of the WT.

The unsaturated zone/saturated zone interface can, in principle, be considered a "well-defined boundary" constituting an electrical and seismic interface. Therefore, it can be determined by different geophysical methods, e.g., electrical resistivity (ER), electromagnetic methods (EM), and seismic methods.

An important aspect to be considered when analyzing and interpreting geophysical data is the presence of capillarity. By definition, the WT corresponds to the depth at which the water would be in the aquifer if it were subjected only to atmospheric pressure. When drilling a borehole, the level at which the water is inside the borehole coincides with the potentiometric level (WT). However, in an undisturbed in situ aquifer, this does not necessarily occur, due to the existence of the capillary fringe. The thickness of the capillary fringe, which can only be observed in the in situ massif and not in the borehole, is directly proportional to the amount of fine-grained material present in the soil. This means that the capillary fringe pressure is greater in clayey soils than in sandy soils (Figure 1). Therefore, the WT is not a sharp interface but, rather, a gradational one (a transition zone) with varying width, dependent on the average size of the grains in the soil.

Determining WT depth through geophysical methods in fine-grained soils (silts and clays) is difficult due to thick capillary fringes occurring at these sites, where the saturated/unsaturated boundary is poorly defined. On the other hand, WT depth can be readily identified in coarse-grained sand and gravel, where there exists a distinct boundary between the saturated and unsaturated zones.

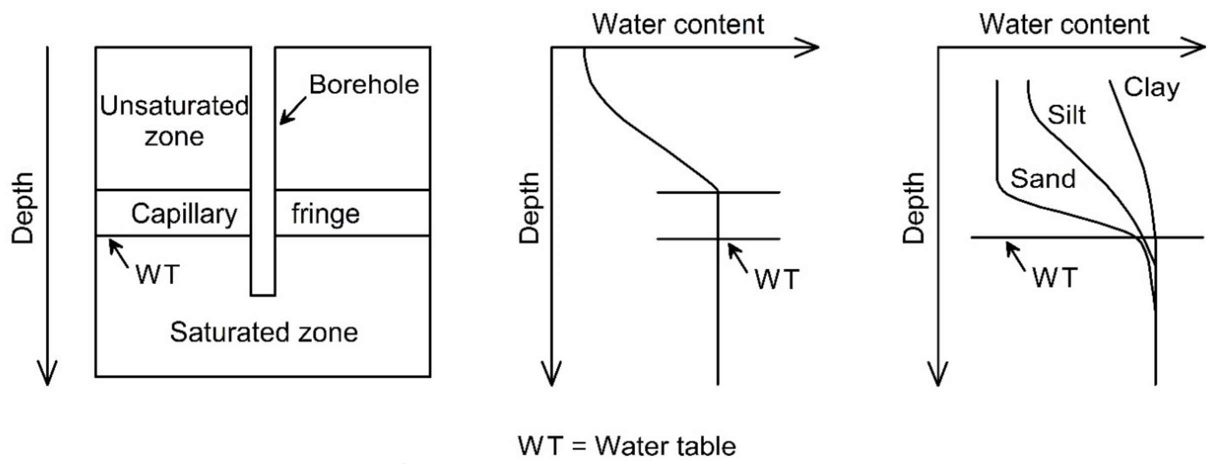

Figure 1: WT transition zone (modified from Annan et al., 1991).

Several authors have claimed that the geophysical signal response, specifically GPR wave reflection, occurs at the top of the capillary fringe and not necessarily at the top of the saturated zone, where the soil pores are completely filled with water (Trenholm and Bentley, 1998; Bentley and Trenholm, 2002; Bano, 2006).

This article discusses the application of some geophysical methods to determine WT depth. The methods it addresses are electrical resistivity, through vertical electrical sounding (VES) and 2D electrical profiling techniques, electromagnetic methods (FDEM and GPR), and seismic methods (refraction, reflection, and crosshole testing).

GEOPHYSICAL METHODS APPLIED TO WATER TABLE IDENTIFICATION

Although there are a lot of papers in the literature related to the use of geophysical methods for groundwater exploration, in crystalline or sedimentary aquifers, there are not so many papers that specifically address the use of the methods for the determination of the shallow WT depth, subjected only to atmospheric pressure in a porous medium. In these cases, the geophysical methods must have sufficient resolution to achieve the objectives. Many papers which were already published a very long time ago address this topic with quality and in-depth discussion of the subject, sometimes not found in more recent papers and, therefore, will be referenced in this article.

GPR

The GPR method is characterized by high resolution and limited depth of penetration. Consequently, hydrogeological studies using this method are restricted to shallow aquifers.

GPR is an excellent method for determining the WT, as the interface between the unsaturated zone and the saturated one constitutes, a priori, a good reflector for the high frequency electromagnetic waves employed by the method. Reflection occurs at the contact between layers displaying contrasting dielectric constants (K) and water presents a high value of this property as compared to geological materials in general (Table 1). Therefore, GPR is one of the methods that respond most efficiently to the presence of water in aquifers.

Table 1: Typical dielectric constant ($K=\varepsilon/\varepsilon_0$) in common geological material at 100 MHz (modified from Davis and Annan, 1989).

Material	K
Air	1
Fresh water	80
Dry sand	3-5
Saturated sand	20-30
Silts	5-30
Clays	5-40

GPR wave propagation does not undergo severe attenuation in permafrosts (frozen soil) and the data obtained in this type of environment show excellent quality, as shown by the GPR data acquired by Davis and Annan (1989) where the WT can be readily visible in the section presented in Figure 2.

However, in tropical soils, many times occurring in Brazil and which generally present low electrical resistivity, the GPR data commonly are not of satisfactory quality.

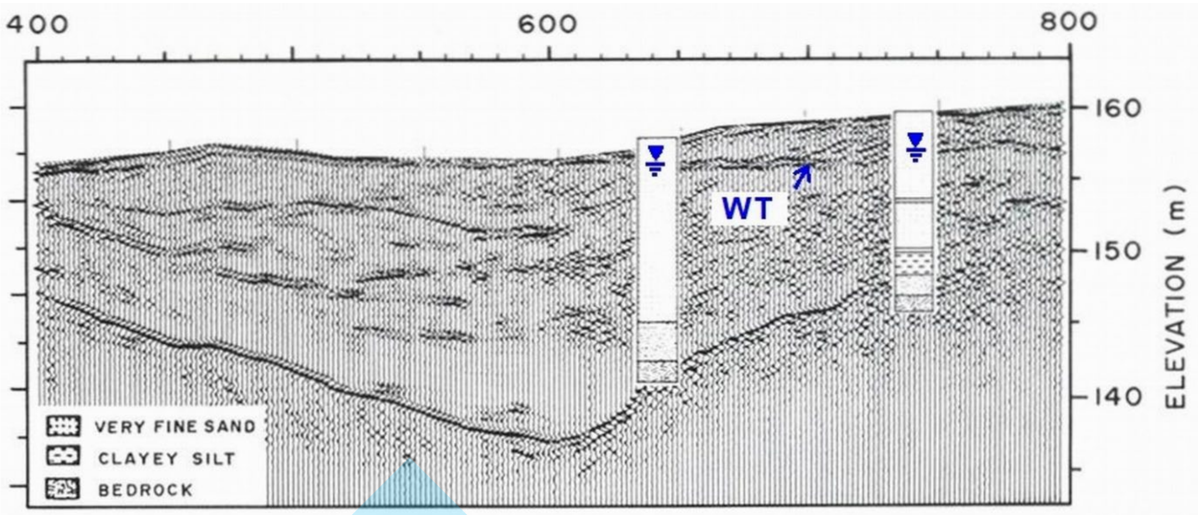

Figure 2: GPR section obtained at a site in Ontario (USA). The geological setting consists of water-saturated fine sand over a granodiorite bedrock. The reflection at the WT is pointed by the blue arrow in the section (modified from Davis and Annan, 1989).

In sandy and coarse-grained soils, where the capillary fringe is narrow, the reflector corresponding to the WT is well defined. Specifically in sand dunes, a favorable environment for propagation of GPR electromagnetic waves, WT reflection is usually strong, sharp and well defined, as can be shown from the data obtained by Pestana and Botelho (1997) at a sand dune near Abaeté Lagoon in Salvador, BA, Brazil, using an 80 MHz antenna (Figure 3).

On the other hand, in fine-grained soils (with presence of silt and clay), where the height of the capillary fringe is larger than in coarse-texture soils, with a smooth transition between the dry and saturated soil, the reflection of GPR signal can be not well defined.

Figure 4 shows a GPR section obtained with a 100 MHz antenna at an embankment where the WT was at a depth of nearly 7 m. The reflection at this depth is not visible, due the clay presence in the embankment, high capillarity and signal attenuation, illustrating the case in which the WT does not constitute a sharp interface, but a gradational one.

Annan et al. (1991) state that “effective WT detection has frequently required use of lower frequencies (25 MHz-100 MHz) than traditionally employed during most GPR surveys”. Johnson (1992) has stated that the distinctness of the saturated zone reflector depends on the sharpness of that boundary compared to the wavelength of the GPR signal transmitted into the ground. Then, the use of multiple frequencies can be a good practice to contribute to a better definition of the reflector corresponding to the WT by using the GPR method.

Nakashima et al. (2001) performed a GPR survey in a site with a very dry soil. The data were collected using the CMP method, instead of the usual common-offset method. The CMP method, which improves the signal-to-noise ratio, allowed determining the groundwater level at approximately 8.0 m depth. Furthermore, through this method it was also determined the vertical dielectric constant distribution from the interval velocities.

Mahmoudzadeh et al. (2012) present surveys using both GPR and ER in sites with shallow WT ranging between nearly 1 m to 3 m (Figure 5). The time-depth conversion of the GPR data was made by using frequency domain reflectometry (FDR) to estimate soil dielectric constants.

FDEM

There are not many concerning FDEM papers that specifically address its use for the WT depth determination, possibly due to its characteristic low vertical resolution. Several papers can be found using FDEM methods in studies of hydrogeology to estimate soil water contents in subsurface, water salinity, among other applications (Boaga, 2017).

However, for the determination of the depth of the WT by the FDEM method, few references were found and some can be cited (Schumann and Zaman, 2003; Sherlock and McDonnell, 2023).

FDEM methods give estimates of overall conductivity in moderately to highly conductive ground and have been widely used for ground water exploration and soil/ground water contamination mapping. They have good lateral resolution when used in profiling mode

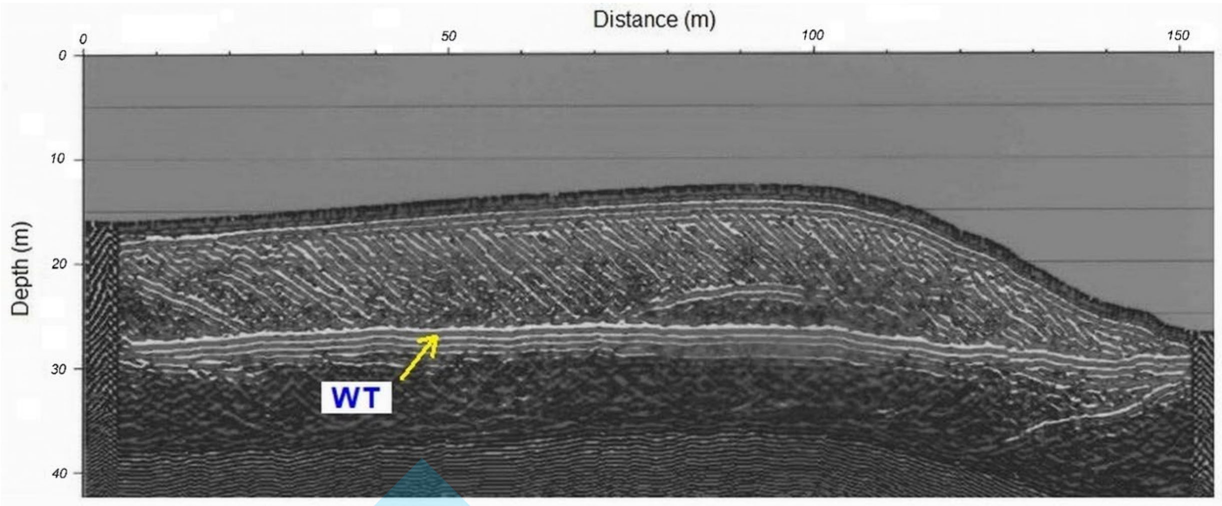

Figure 3: Migrated GPR section with topographic correction obtained at a sand dune, indicating WT reflection (modified from Pestana and Botelho, 1997).

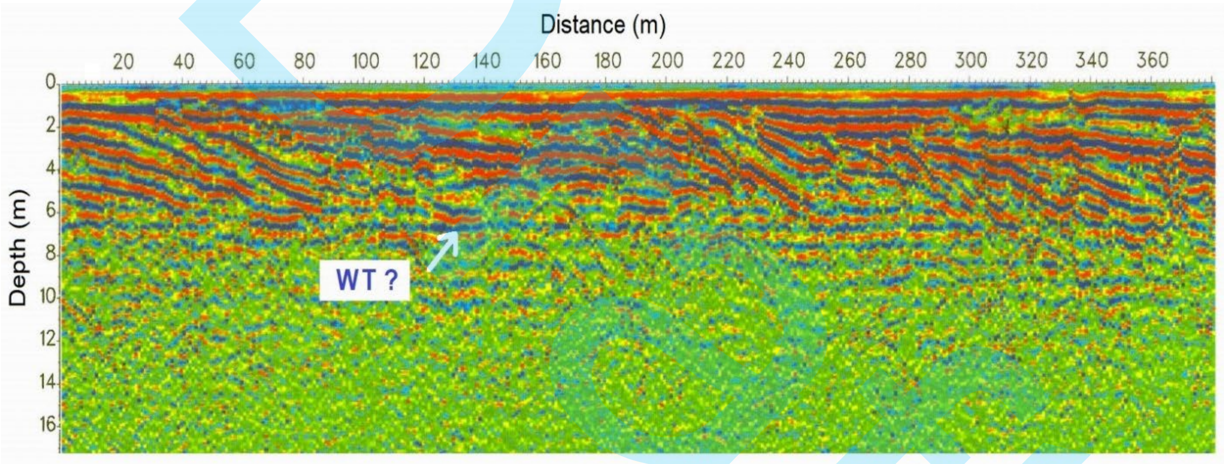

Figure 4: GPR section obtained at a landfill where the WT was at a depth of nearly 7 m, without clear definition of the reflector corresponding to this interface.

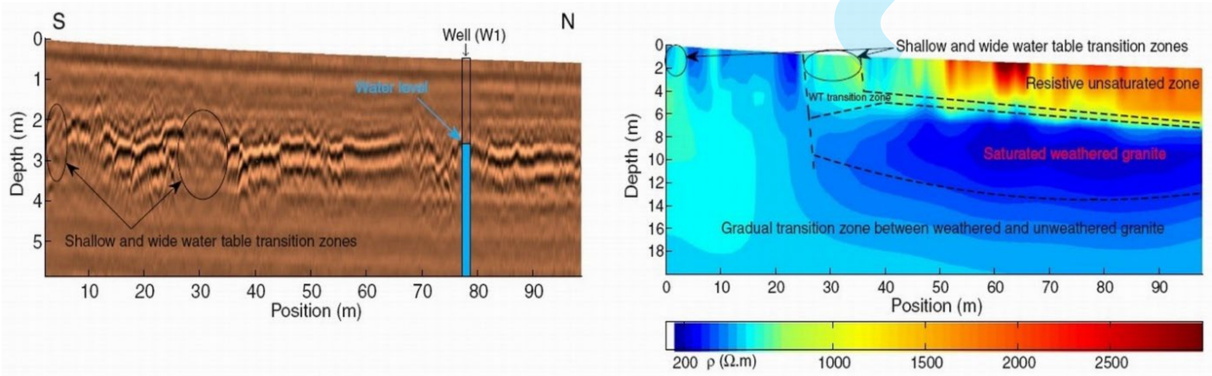

Figure 5: GPR section (left) and 2D modeled resistivity section (right) obtained by Mahmoudzadeh et al. (2012).

(McNeill, 1990). On the other hand, the FDEM method has the disadvantage of low vertical resolution if compared with the ER method. The method can be used to obtain depth information by taking measurements at different intercoil spacings, multiple frequencies and different coil orientations.

The article presented by Monier-Williams et al. (1990) shows an application of the FDEM method in studies of groundwater contamination in three sites in Brazil. In two sites, the authors observed that topography-related anomalies dominated the apparent terrain conductivity contour maps. According to the authors, these anomalies were related to the variable depths to conductive horizons (for example, the WT or clay strata) and then it was proposed a topographic correction procedure.

Electrical Resistivity

The ER method has been in use for a long time in groundwater-related applications (Breusse, 1963; Loke et al., 2013). Sufficient contrast of physical properties of saturated and unsaturated soil (due water content, mainly) can lead to good conditions for ER surveys. ER responds well to the presence of water because, in general, saturated soils present lower resistivity than unsaturated ones do, grained soils considered.

The data can be acquired by two different modes: VES and 2D electrical profiling. The VES is a typical one-dimensional (1D) survey which determines the resistivity variation with depth at a given point. It is assumed the assumption that the resistivity distribution does not vary laterally. The VES produces valid results for layered terrains. On the other hand, it produces inaccurate geologic models in complex geologic environments.

The two-dimensional (2D) electrical profiling can produce more realistic models to map lateral resistivity variations and, consequently, is more suitable for more complex geologic environments. Advances have been made in 2D electrical surveys in recent years (better instrumentation, cost efficient field acquisition techniques and better available inversion softwares). Consequently, nowadays it is possible to acquire large amount of ER data in a short time using different type of arrays and produce reliable subsurface models.

The literature has reported the use of ER in many studies of water availability and quality (determination of aquifer geometry and vulnerability, detection of contaminants in soil and groundwater, and salinity surveys) when WT depth must be known in advance (Ward, 1990; ASTM D 6431, 2005).

Barker and Moore (1998) present a groundwater investigation using ER for time-lapse studies (infiltration and pumping) of the shallow aquifer. The 2D subsurface distribution of resistivity, with sharp boundaries, was obtained by inversion showing the position of the WT. Vertical electrical sounding data, namely depth and resistivity of the layers, were used to constrain the inversion process.

Oliva and Kiang (2004) used 139 VES in a survey performed in Rio Claro municipality, São Paulo State, Brazil. A potentiometric map was made using the depths of the WT (between 2 m and 26 m) obtained from the results of the VES.

Kalinski et al. (2018) performed combined VES survey and sampling of shallow water wells in Leogane, Haiti. The top of the WT was interpreted based on drops in electrical resistivity with depth. An overall map showing the depth to the WT throughout the entire city of Leogane was created.

In a case study for road site characterization, Al-Heety et al. (2021) presented a 2D modeled section with a well-defined interface between high resistivity topsoil dry zone and conductive saturated zone bellow (Figure 6). According to the authors, the high-water table is one of the factors that can be responsible for the road failures related to the geological factors. The 2D modeled section showed the WT very shallow (depths between 2.0 m and 2.5 m).

Seismic methods

Seismic refraction surveys can be successfully applied to explore subsurface exhibiting a low number of layers, where the seismic velocity increases with depth. In hydrogeological applications, using P-waves, this situation is generally found.

Water saturated sediments have higher P-wave velocities than partially saturated ones. Typically, P-wave velocities are less than 600 m/s in unsaturated media above the WT and approximately 1,500 m/s below the WT, granular media assumed. Then, P-wave refraction surveys can be employed to determine WT depth. However, its feasibility depends on site conditions.

The statement that “a layer presenting a P-wave velocity of nearly 1,500 m/s is an indication of saturated zone” may be sometimes flawed, because this layer could be a weathered and dry zone, for instance. The use of only P-waves presents some difficulties, such as distinguishing the WT from lithological changes. In this case, the investigation can be performed with combined P- and S-wave surveys. Usually, S-wave velocities are little changed by water saturation so they better represent

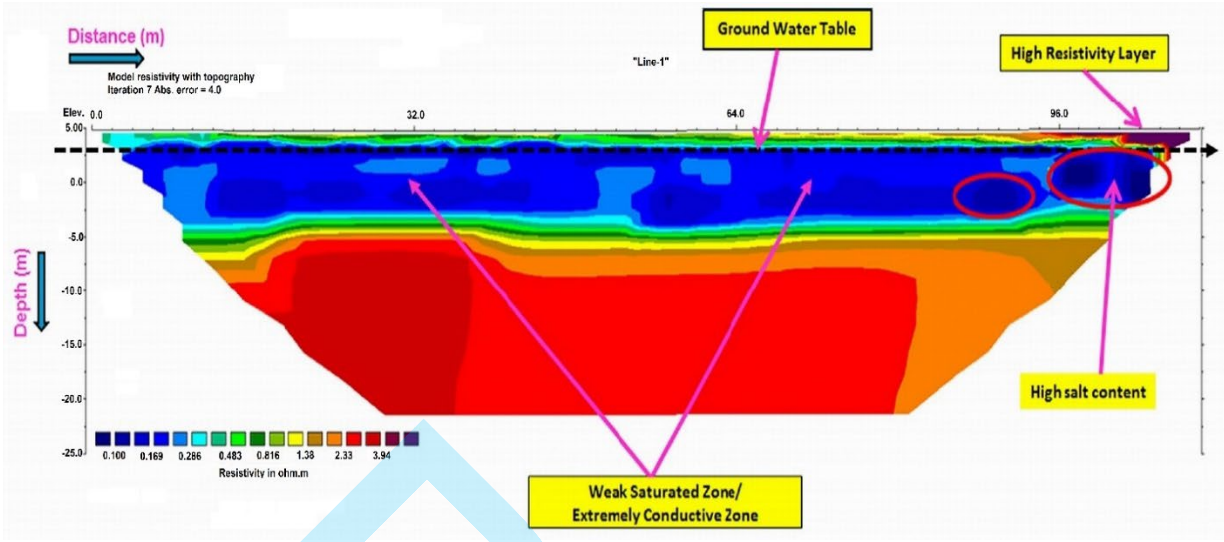

Figure 6: 2D modeled resistivity section obtained by Al-Heety et al. (2021).

lithological contrasts below the WT than P-waves. Adding shear waves to a seismic survey helps resolve this ambiguity, due to saturation having virtually zero effect on S- wave velocity (Dobecki, 1988).

Several studies have showed that the combined use of both P-wave and S-wave, especially by estimating VP/VS or Poisson's ratios, may be a good practice to assess the saturation of the medium and, consequently, determine the depth of the WT (Turesson, 2007; Grelle and Guadagno, 2009; Pasquet et al., 2015).

It is worth noting that some researchers have even suggested that S-wave velocity decreases upon full saturation.

Seismic reflection relies on contrasting densities and velocities and can be employed to determine WT depth. When investigating a site where the WT was over 30 meters deep, Dobeki (1988) shows the reflection section (using P-wave) in which a reflector corresponding to the WT is well defined (Figure 7). However, at a site where the WT is shallower (around 10 m), while the reflector is well defined in the S-wave section, it is not so in the P-wave section.

Cardimona et al. (1998) made use of both seismic reflection (using P-wave) and low frequency GPR (using 25 MHz antenna) to investigate a shallow, unconfined aquifer. Neither method was capable of defining a reflection from the WT, probably due to water saturation increasing over a thick zone. The authors also claim that it is uncommon to obtain good quality seismic and GPR data at the same site, and that "collecting good-quality seismic data from the upper 15 m is usually difficult".

Miller and Genau (1991) present the result of a reflection seismic survey where reflection signals from the WT were obtained at 10.7 m, later confirmed by drilling.

Self-Potential (SP)

The self-potential method has been used for investigation of groundwater movement by determining the direction of groundwater flow. The SP sources are related to electrochemical, thermoelectric and electrokinetic (streaming) potentials. The last one (streaming potential) is associated with ground water flow.

For most cases, interpretation of SP data is based only on a qualitative analysis of the results, which provide sufficient information to delineate groundwater flow. The data are usually presented as contour maps, showing a plane view (XY) of equipotential values, with no information concerning depths (Z). Therefore, the WT depth cannot be determined from SP data through only qualitative analysis.

For seepage flow in a uniform permeable medium, the streaming potentials reflect the contours of the WT. The potentials grow in the direction of water flow and their intensities are proportional to the hydraulic gradient (Bogoslovsky and Ogilvy, 1973). Thus, an SP equipotential curve map provides information about flow configuration, direction, and intensity (Gallas, 2020), but not information about depths.

However, some authors have presented papers showing how to obtain more quantitative information from SP data. Fournier (1989) used the potential field

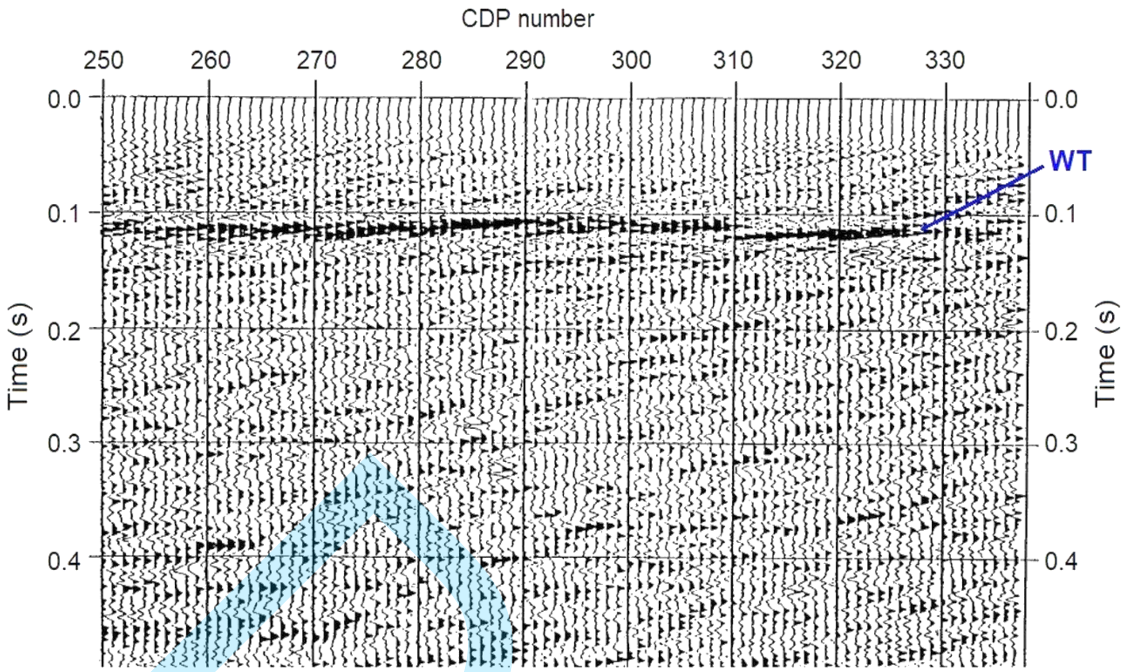

Figure 7: P-wave reflection CDP section showing a coherent event at 0.110 s as corresponding to the deep water table (modified from Dobecki, 1988).

theory to develop a relationship between the SP signals measured at the ground surface and the position of the WT for an unconfined aquifer.

Jardani et al. (2009) proposed a method for inverting SP data to determine the shape of the WT in steady-state conditions of pumping or injection tests.

CASE STUDIES AND DISCUSSION

FDEM

FDEM methods provide lower vertical resolution compared to that provided by the ER method. However, information, only qualitative, can be obtained and, consequently, the method cannot be used effectively to determine the depth of the WT.

A 380 m FDEM profile was acquired with the Geonics EM-34 equipment, measures taken every 10 meters. The geology of the site, identified by two percussion drillings (BH-1 and BH-2, 60 m apart and nearby the FDEM profile), mainly consists of an embankment (nearly 2 m thick) over embedded layers of fine silty sand/fine sand and clay. The WT depth at the site was about 13 m (Figure 8).

Figure 9 shows apparent electrical conductivity (σa) profiles obtained by a FDEM survey. The combined use of 10 m and 20 m extension cables, associated with two possible modes for conducting the measurements (with dipoles at horizontal and vertical positions), allowed obtaining data down to depths of 7.5 m, 15 m, and 30 m, according to exploration depths for EM34 at various intercoil spacings (McNeill, 1980).

It should be noted that the data corresponding to depth of 30 m (in green), with higher σa values, are strongly influenced by the saturated zone, which cannot be observed at the profiles corresponding to depths of 7.5 m and 15 m (in blue and purple, respectively).

A simple qualitative analysis of these data, without the previous knowledge of the depth of the WT, would only allow us to suppose that the WT depth would be between approximately 8 m and 15 m deep, using a criterion that the effective investigation depth is half of the exploration depth, illustrating in this case study the low vertical resolution of the FDEM method.

ER

Among the geophysical methods used to determine WT depth, ER, employing both the VES and 2D electrical profiling, is very efficient.

Figure 10 shows an example of a 2D modeled section of ER obtained by the author at a site consisting of silty fine- and medium-grained sand, with WT at depth of 7 m to 8 m, confirmed by two boreholes. A zone of low electrical resistivity below 8 m is well defined at the center of the section and corresponds to the top of the saturated zone. This case illustrates a usual interpretation procedure to identify the saturated zone of the terrains, commonly associated with low electrical resistivity zones observed at 2D ER modeled sections.

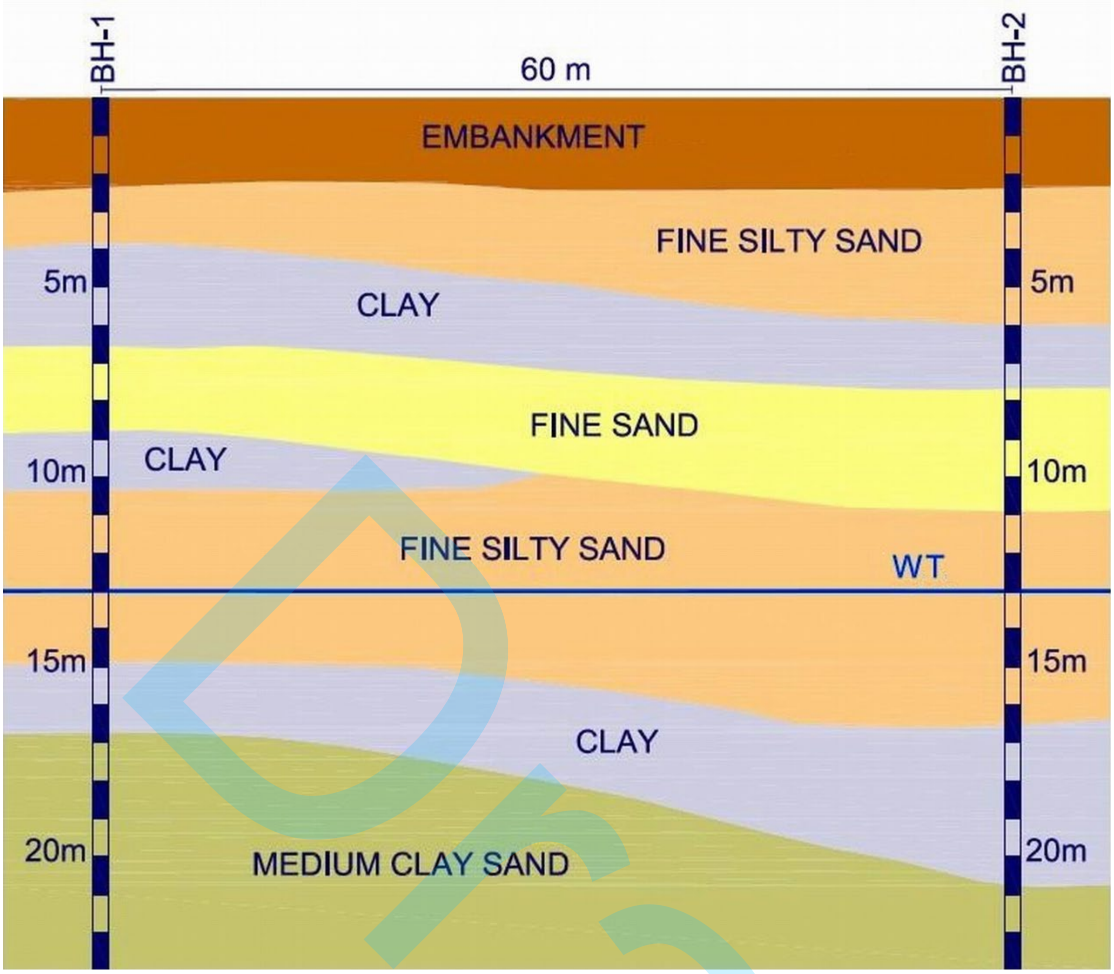

Figure 8: Geological section derived of two drilling data nearby the FDEM profile.

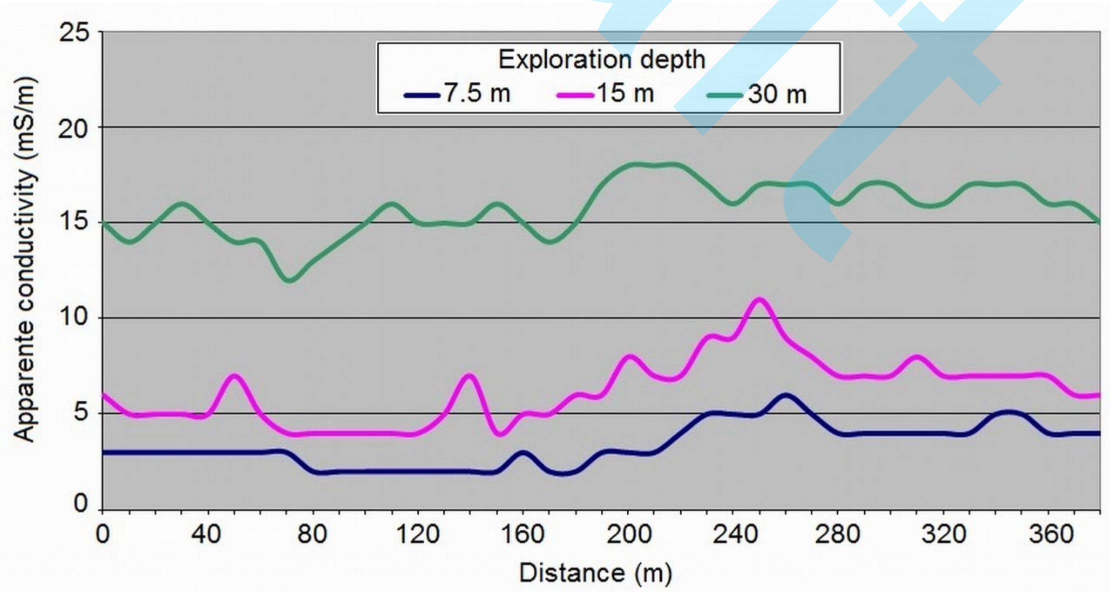

Figure 9: FDEM profiles obtained with EM-34 equipment (Geonics) at three different exploration depths.

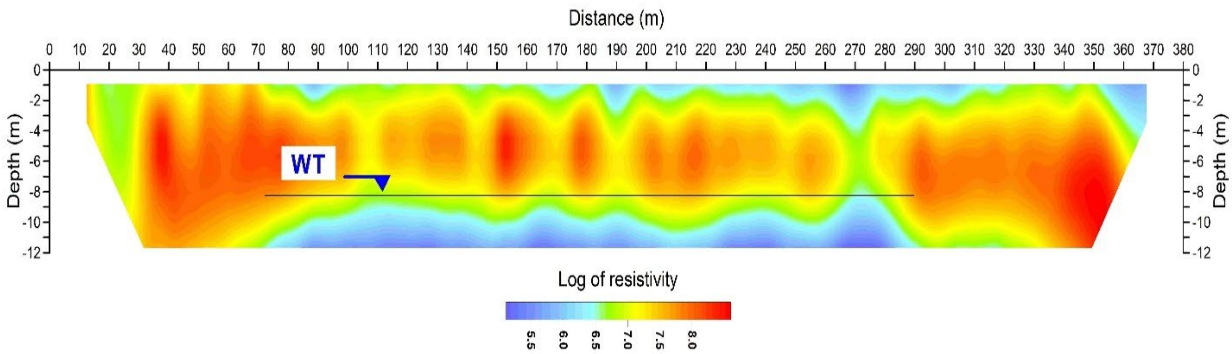

Figure 10: 2D modeled resistivity section obtained at a site with WT depth at 7 m to 8 m.

However, at sites where clayey soils occur, interbedded with sandy layers, interpretation of ER data by solely identifying a layer with low electrical resistivity in the 2D modeled section may not be so simple and direct, as the following example will show (Gandolfo, 2007).

Along a 40 m profile, it was performed two VES measurements (Figure 11) and one 2D electrical profiling with a pole-dipole array and multiple spacing between electrodes (1 m, 2 m, and 4 m) (Figure 12).

There were shallow boreholes and a trench, which allowed for good geological and hydrogeological knowledge of the site. The depth of the WT was found at 3.3 m.

Figure 13 shows a detail of the 2D modeled resistivity section shown in Figure 12, correlating with the stratigraphy of the site and showing the position of the WT depth. It may be observed that the WT is on top of the high electrical resistivity layer (layer with resistivity ρ_3, in green) and not on top of the low electrical resistivity layers (layers with resistivity ρ_2 and ρ_4, in blue). The unsaturated plastic clay layer above the WT exhibited a lower electrical resistivity value (ρ_2) than the saturated sandy clay layer below (ρ_3).

Seismic methods

The seismic method that most accurately determines the depth profile of V_P and V_S is the crosshole testing (ASTM D4428, 2007), which, interestingly, is better known to civil engineers than to geophysicists.

A crosshole testing was carried out at a site with occurrence of sandstone rocks. Figure 14 shows samples from drill cores of one of the three boreholes used for the crosshole testing.

Above the sandstone there are layers of sandy clay and an interbedded layer of round pebbles. The WT depth was identified by drillings at 7 m. Figure 15 shows the crosshole testing results overlaid with the geological profile of the area.

The V_S vs. Z profile (in red) shows how V_S is little sensitive to terrain saturation, unlike the V_P vs. Z profile (in blue), which is strongly influenced by the presence of water, showing values of the order of 1,500 m/s below the WT in the saturated sandy clay layer.

The next presented example illustrates the application of the seismic refraction method for determining WT depth (Gandolfo, 2014). Data were obtained through the combined use of P-waves and S-waves (SH-shear-horizontal waves, specifically) in order to reduce interpretation ambiguities, as aforementioned.

At the site it occurs soils from the weathering of gneiss and migmatite rocks, namely a red silty clay surface layer. There was a borehole nearby the seismic profile indicating the WT at around 4 m depth. Figure 16 shows the modeled P-wave section resulted of the data processing using the conventional technique based on the delay-time method. The layer with velocity about 1.5 m/ms (in blue) corresponds to the saturated zone of the terrain below the WT, whereas the two upper layers (in purple and orange) correspond to the unsaturated zone.

Supposing that the direct information (borehole) was not available. Then, the layer with V_P about 1.5 m/ms could have been interpreted not as a saturated zone, but as a lithological change. However, by combining V_S and V_P data, this ambiguity could be resolved.

The graph presented in Figure 17 shows the Poisson's dynamic ratio (ν) vs. V_P/V_S ratio. It can be observed that the values of ν are larger than 0.45 when the V_P/V_S ratio exceeds 3.0. In the study site, the resulted V_P/V_S ratio was 3.75.

Figure 18 shows the results obtained by tomographic inversion of the P- and S-wave data. The

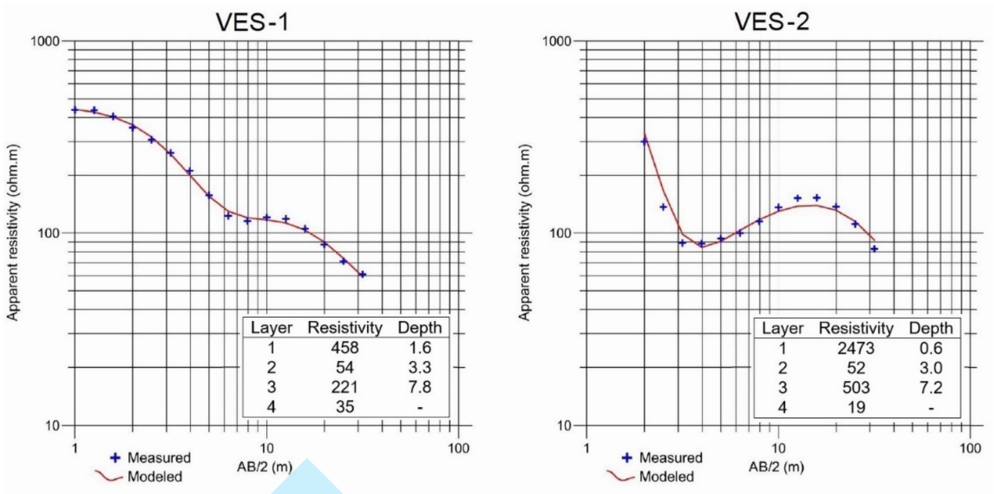

Figure 11: VES measurements performed at 12 m and 25 m positions of the ER profile (40 m extent) whose modeled 2D resistivity section is shown in Figure 12.

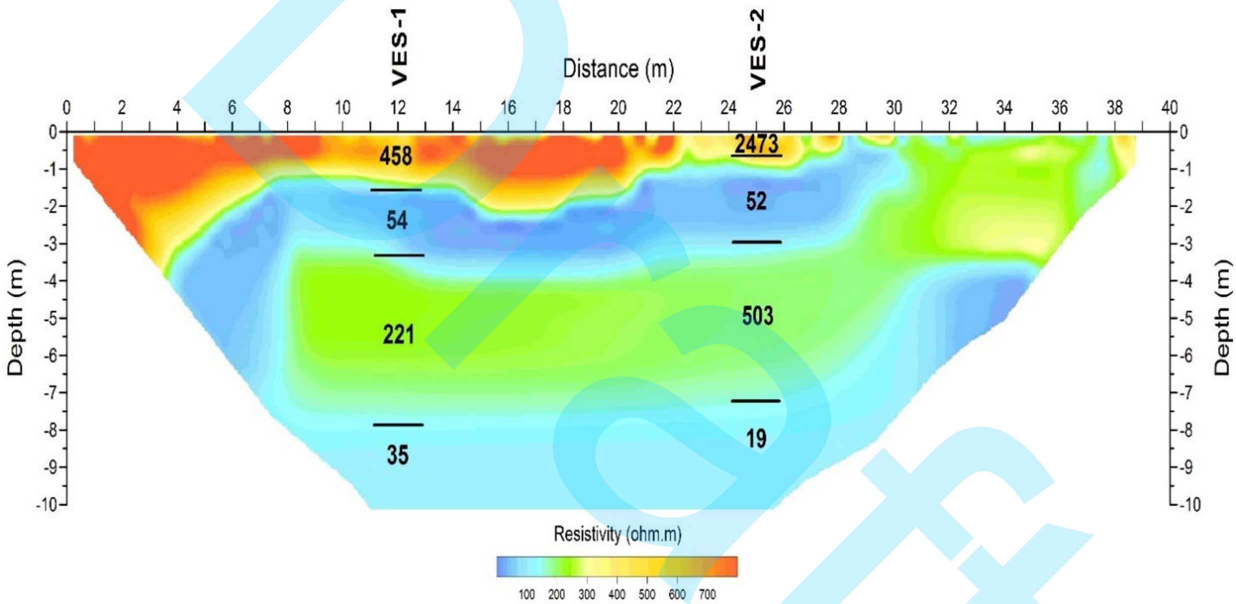

Figure 12: 2D modeled resistivity section with resulting VES-1 and VES-2 models overlaid.

depths are overestimated in the resultant model for P-waves (Figure 18a) because it can be observed that the contour curve of 1.5 m/s is positioned very below the WT depth (4 m). Figure 18b presents the S-wave model.

The same grid layout of the modeled P-wave and S-wave sections (Figure 18c) enabled the estimation of Poisson's dynamic ratio (v) expressed by equation 1.

$$\nu = \frac{\left(\frac{V_P}{V_S}\right)^2 - 2}{2\left(\frac{V_P}{V_S}\right)^2 - 2} \qquad (1)$$

The resulted section, presented in Figure 18d, shows the 2D distribution of v. The section clearly indicates the saturated zone in the terrain, where v values are higher than 0.45 (in blue). The location of the WT is indicated in all sections.

CONCLUSIONS

Identifying the water table and determining its depth through indirect investigation (geophysical methods) is not an easy task as the transition zone between the unsaturated and saturated zones, represented by an interface corresponding to the WT, is not a sharp interface but rather gradational, with varying width.

GPR is an effective method to identify shallow WT depth in sandy soils. The ER method, by using both VES and 2D electrical profile, is very effective too in many cases. Surface seismic methods can present advantages by combined use of P-wave an S-wave to determine de depth of the WT.

It is always recommended the combined use of geophysical methods (ER, GPR, and seismic methods) to resolve ambiguities and provide reliable data for determining WT depth more efficiently.

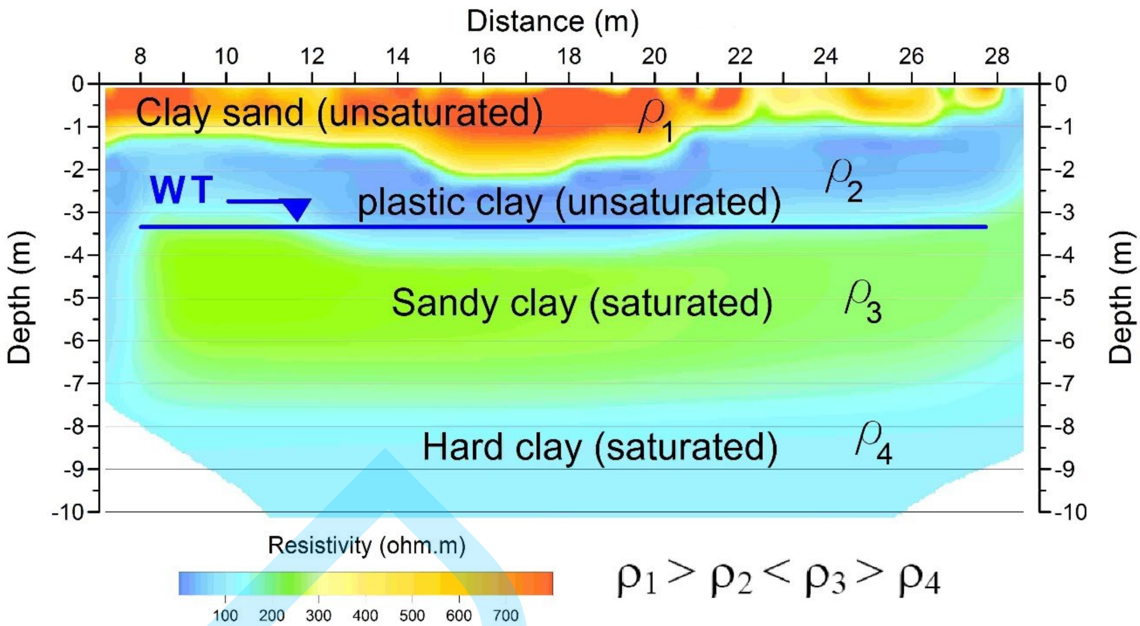

Figure 13: Detail of Figure 11 showing four geoelectrical strata identified in the model, with soil stratigraphy description of the site (WT indicated in blue).

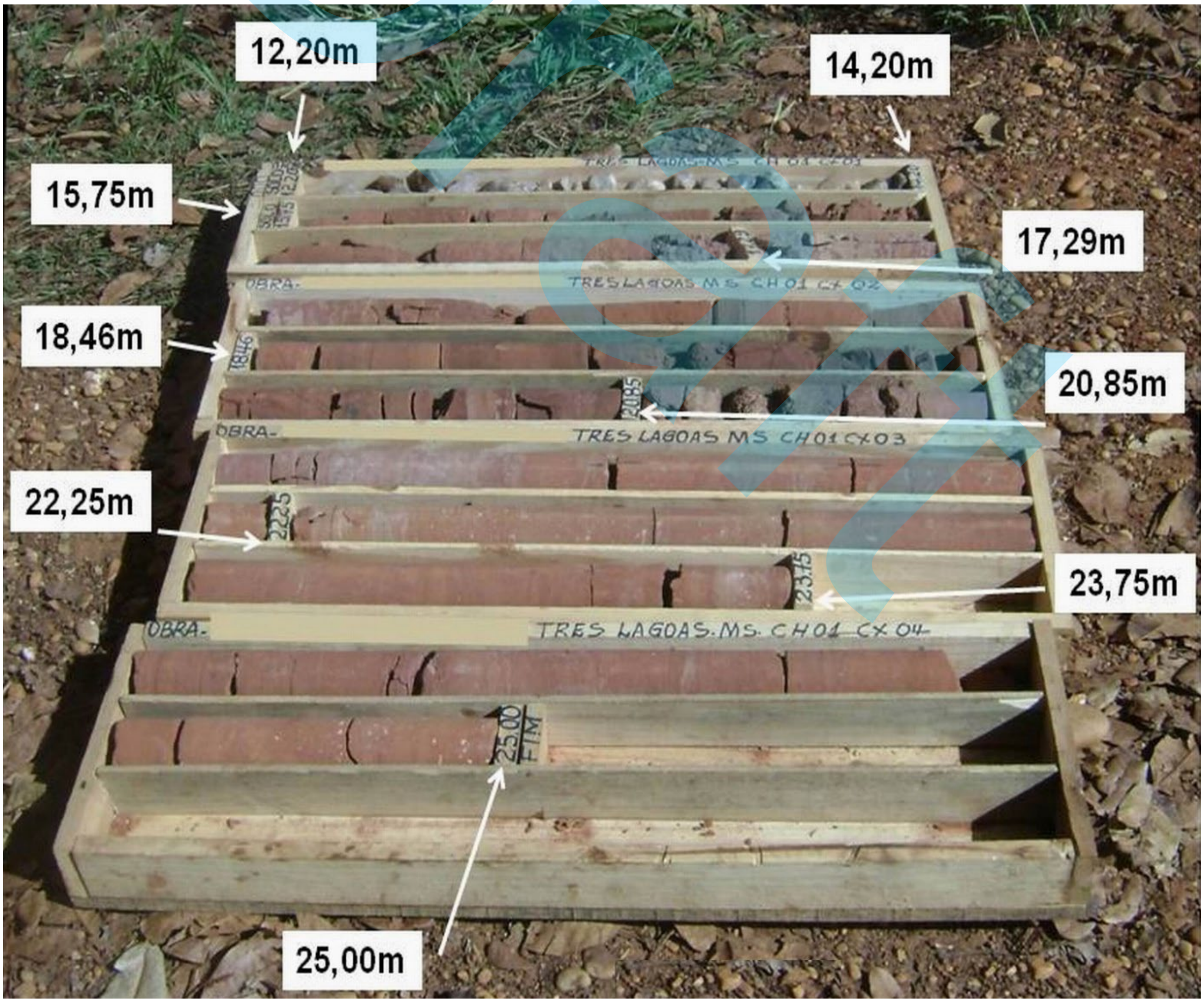

Figure 14: Samples obtained from drilling used for the crosshole testing.

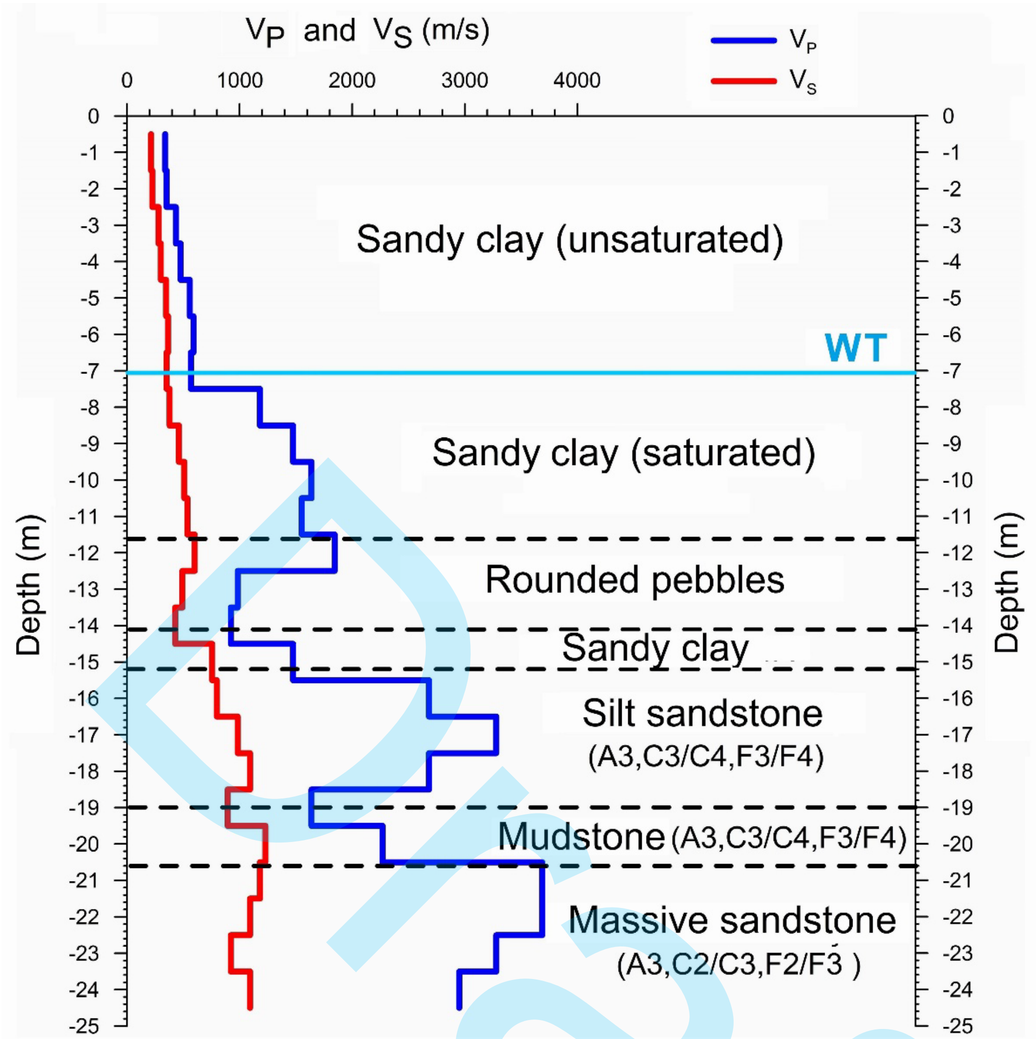

Figure 15: Crosshole testing results and the geological profile of the site.

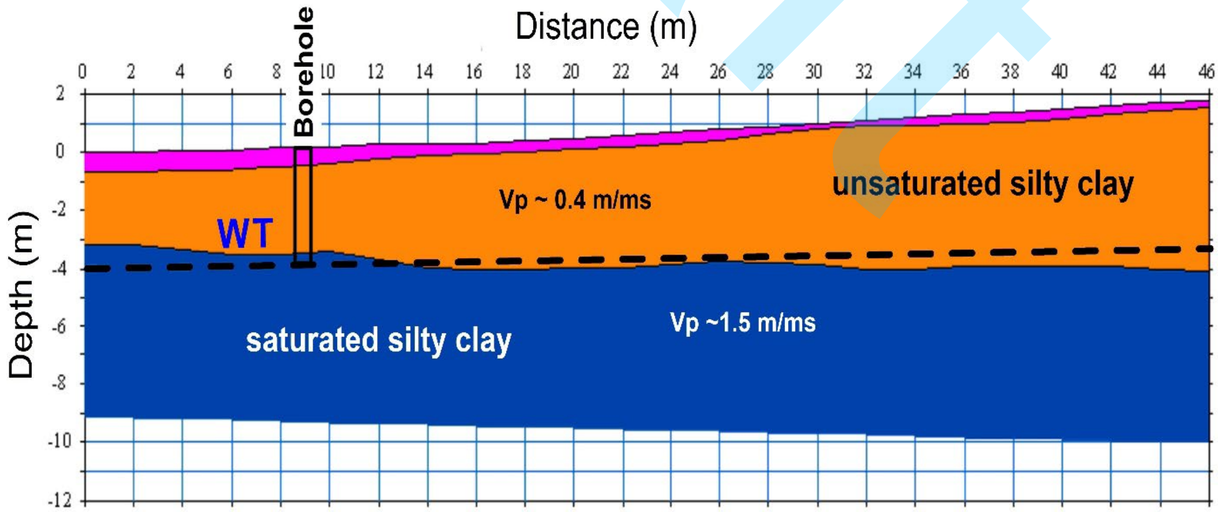

Figure 16: Seismic refraction model (P-wave) resulted from processing based on delay-time method (modified from Gandolfo, 2014).

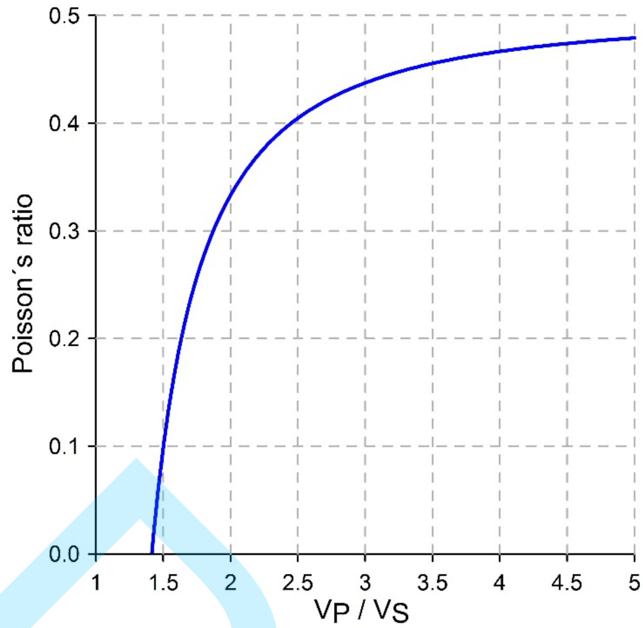

Figure 17: Poisson's ratio (ν) vs. V_P/V_S.

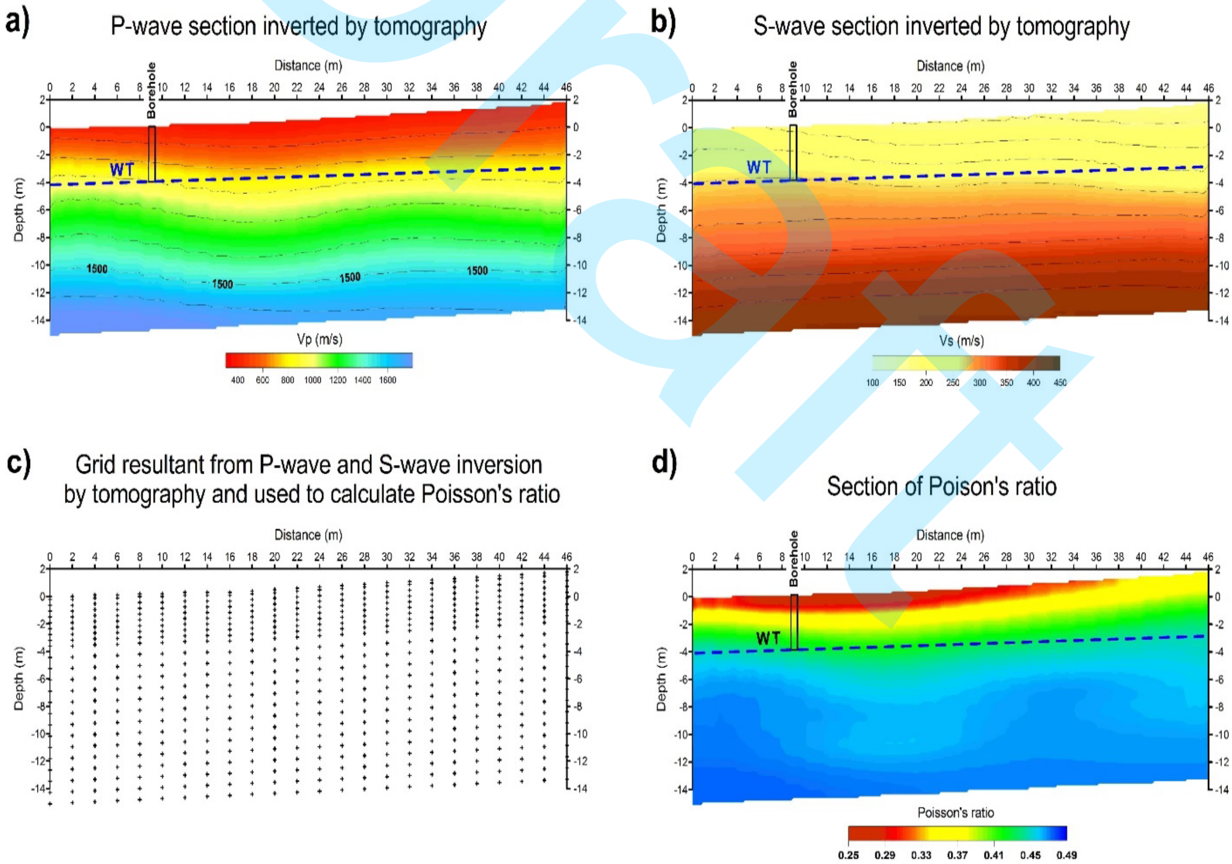

Figure 18: Refraction section models obtained from tomographic inversion: a) P-wave; b) S-wave; c) Grid used to calculate Poisson's ratio; d) Poisson's ratio final section (modified from Gandolfo, 2014).

ACKNOWLEDGMENTS

The author is thankful to the anonymous reviewers for their contributions to improve this paper.

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GANDOLFO, O.C.B.: The author confirms sole responsibility for the study conception and design, data collection, analysis and interpretation of results, and manuscript preparation and writing.

Received on August 9, 2022 / Accepted on May 6, 2023