TEM survey using fixed-loop array applied to groundwater exploration at Taubaté basin: Preliminary results

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Abstract

In this research was used the Transient Electromagnetic Method (TEM) aimed at groundwater exploration in Taubate sedimentary basin. TEM data were acquired through fixed transmitter loop and a 3D mobile coil receiver (fixed-loop array). Also a Vertical Electrical Sounding (VES) was acquired in order to reduce the ambiguities in the interpretation of the results by using TEM/VES 1D joint inversion. TEM 1D Individual inversions were interpolated in order to generated the transversal profile. The result of a 2D pseudo-section permit to map the electric resistivity distribution of the study area, defining the shallow sedimentary aquifer.

Introduction

The Transient Electromagnetic Method (TEM) was developed in the 1980s and since then has been widely used like a robust method of geophysics exploration, which electrical and magnetic fields are induced by transients pulses (McNeill, 1990). The use of this method to mineral exploration and hydrogeological studies had a substantial increase in the last years due to the versatility and great sensitivity to found conductor layers in subsurface.

TEM is a very useful method to mapping subsurface at deep depths and to detect conductive layers. However, it is limited to investigate shallow layers, causing a gap in interpretation. On the other hand, VES is an important electroresistivity technique to map shallow layers and to detect resistive layers. This way, both TEM/SEV are necessary to corroborate geoelectrical information and to understand the geology of any study area. TEM 1D Individual inversions were done using an IX1D (Interprex Ltda) commercial software to generate a 2D pseudo-section by interpolation. It was useful to observe the resistivity information of layers along of the profile. TEM/SEV 1D joint inversion was done using Curupira software (Bortolozo and Porsani, 2012) for the central sounding to corroborate with 2D pseudo-section interpretation and to detect with more accuracy the geoelectrical information of shallow layers.

Previous work has shown how the TEM method was useful in the mapping of sedimentary aquifers and the search for fracture zones within the basalts of the Serra Geral Formation, Paraná basin (Bortolozo, 2011; Porsani et al., 2012a, 2012b), among others.

In this paper the aims are mapping the geoelectric stratigraphy of the Taubaté basin, in order to determine the thickness of the sedimentary layers, identify shallow sedimentary aquifer and to locate fractured zones (semi-grabens).

Study Area

The study area is located around Taubaté city, state of São Paulo. Geologically, this area is seated over Taubate sedimentary basin (Figure 1), located in east portion of São Paulo state, between Mantiqueira Mountain Range and Serra do Mar Range. The Taubaté Group is composed by Resende, Tremembé and São Paulo Formations. The tectonic structures present in the study area suggest successive changes in the tensions field of the Taubaté basin, which began in the Neogene-Quaternary (Mancini, 1995)

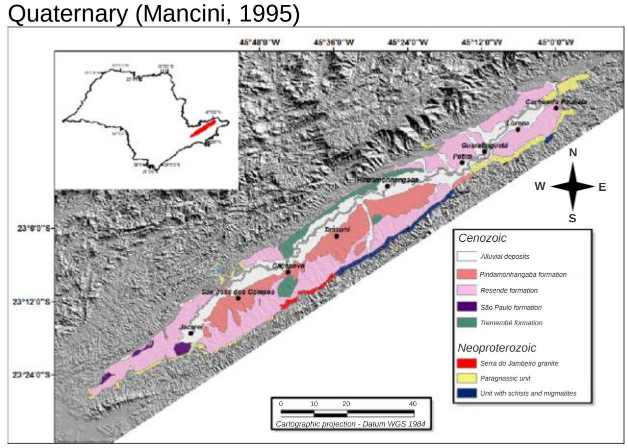

Figure 1: Taubaté sedimentary basin according to groundwater map of São Paulo State (Souza Filho, *et al.,* 2012. Modified by CPRM, DAEE, IG e IPT, 2005. Adapted).

The Taubaté basin is part of a set of basins belonging to the continental rift of southeast Brazil (Riccomini, *et al.,* 2004), related to distensive tectonic of tertiary age. This basin is seated over igneous and metamorphic rocks from

Ribeira belt dating from Paleoproterozoic until Neoproterozoic (Hasui and Ponçano, 1978).
The elongated shape of the Taubate basin is conditioned by old discontinuities of the east-northeast (ENE) direction of the basement, which favors a resurgent tectonics. The basin framework is formed by semi-grabens, which one could be interesting structures to groundwater exploration, separated by transfer or accommodation zones, with inverted depocenters and alluvial fans associated with edge faults, in typical rift-type basin geometry (Vidal, A. C. *et al.*, 2004).
The subdivision that the basin was submitted is compound by sedimentary patches of variable granulometry, since sandy portion located near to Jacareí city until the clayey portion located near to Pindamonhangaba city, this last one characterized by Tramembé formation of Oligocene age (Souza Filho, *et al.* 2012).
This basin present many segmented blocks (São Jose dos Campos, Taubaté, Aparecida) separated by Pindamonhangaba and Caçapava highs and failures (Jacaréi, São José, Bom Retiro, Quiririm, Ribeirão da Serra, Piedade e de Aparecida).
The Jacareí-São José dos Campos subdivision present a maximal depth of 300 meters and is compound by rocks of Resende formation; The Quiririm-Taubaté subdivision ranges a maximal depth of 600 meters and its composition is predominantly of sandstone and conglomerates at the edges and shales at central part. The Aparecida-Lorena subdivision present a maximal depth of 800 meters, to west and it is predominantly compound of lacustrine sediments and to east sediments of fluvial origin (Vidal, *et al.,* 2004).

Methods

According McNeill (1994) and others, TEM method uses a transient source signal, transmitter loop and a receiver coil. In this transmitter loop there is a direct current which generates a constant magnetic field which pass through any conductor of subsurface. The idea of this method is that, if the current was turned off the magnetic flow will be zero, in the other words, this flow vary until get a null value (Figure 2). So that, according to Neumann's Law, will be generated secondary currents on the conductor. This way, the secondary field, which one depends on time and induces an electromotive force, decay with the time as they the current dissipates in the subsurface (Figure 3), phenomenon known like "Smoke rings". This dissipation vary according to electric resistance that the conductors presents in the subsurface, providing geoelectrical properties under the field array. The apparent resistivity value is calculated from the electromotive force value as (Kaufman and Keller, 1983):

$$\rho = k\left(\frac{M}{V(t)}\right)^{2/3}\frac{1}{t^{5/2}} \qquad (1)$$

Where:

- *M*: Magnetic momentum (Am²);
- *t*: Time (s);
- *k*: Constant calculated by:

$$k = -\frac{\mu_0}{\pi}\left(\frac{an}{20}\right)^{2/3} \qquad (2)$$

$\mu_0\ (4\pi\, x\, 10^{-7}\ H/m)$ is the magnetic permeability of the vacuum, a and n are effective area and the number of wire loops in the receiver coil respectively.

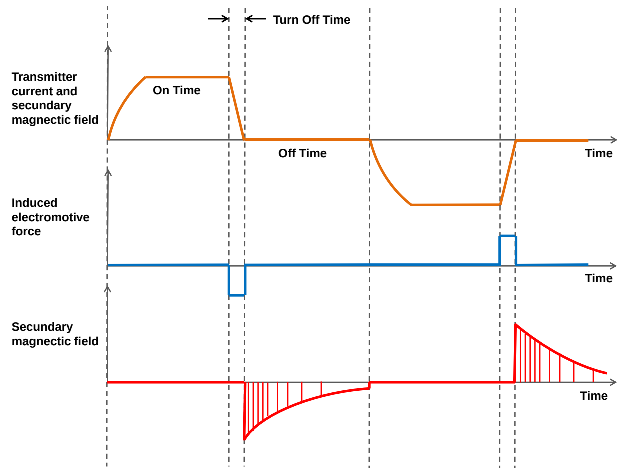

Figura 2: Scheme representative of the events in a TEM sounding (Kirsch, 2006. Adapted).

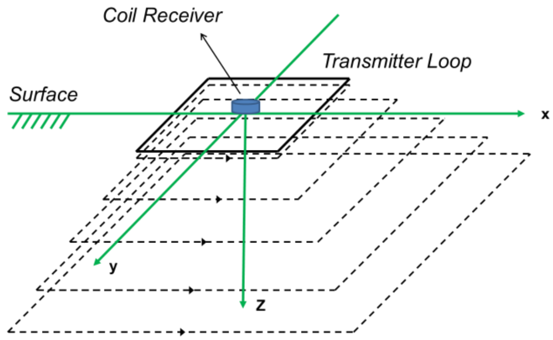

Figure 3: Secondary currents generated in subsurface (Adapted from McNeill, 1994).

Electroresistivity Method is based on the determination of electrical resistivity of materials in subsurface.
This method consists of injecting electric current into the ground through metal electrodes inserted in the surface (current electrodes - AB), and measuring the potential resulting in pairs of electrodes (potential electrodes - MN). Electrical resistivity values can be estimated because the arrangement of the electrodes is known. According to Koefoed (1979), the apparent electrical resistivity of the subsurface can be expressed as:

$$\rho_a = K\frac{\Delta V}{I} \qquad (3)$$

Where:

- ρ_a = Apparent resistivity electrical (Ohm.m);
- ΔV = Difference of potencies (V);
- I = Current (A);
- K = Geometric coefficient calculated by:

$$K = \pi \frac{(\overline{AM}\ \overline{AN})}{\overline{MN}} \qquad (4).$$

In this research was used the VES vertical electrical sounding that describe the distribution of this property as a function of depth and horizontal distance. VES and TEM data was combined to reduce the existing ambiguities in the data interpretation that allow a geoelectrical model more reliable.

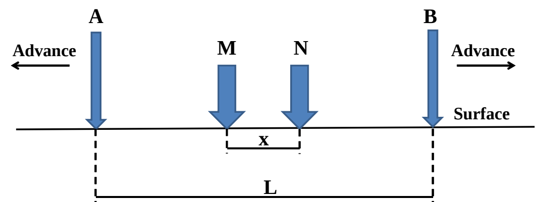

Figure 5: Schematic drawing of a Schlumberger arrangement used to acquire VES data.

Acquisition and processing data

TEM sounding was acquired using a transmitter fixed loop array (TX), arranged in the square form with 200 meters of side. The receiver coil mobile (RX), in which it travels along the N-S direction of 150 m length inside of loop (Figure 4). The data was acquired with PROTEM-D register and a transmitter source TEM57-MK2, which has three different frequencies of data acquisition (30Hz, 7.5Hz and 3Hz), which allows reach ~600 meters of depth depending on the electrical conductivity of the subsurface layers.

The location of study area in UTM is: Zone 23K; V1: 448259.00 m E, 7452682.00 m S; V2: 448462.00 m E, 7452688.00 m S; V3: 448469.11 m E, 7452490.06 m S; V4: 448267.36 m E, 7452483.60 m S.

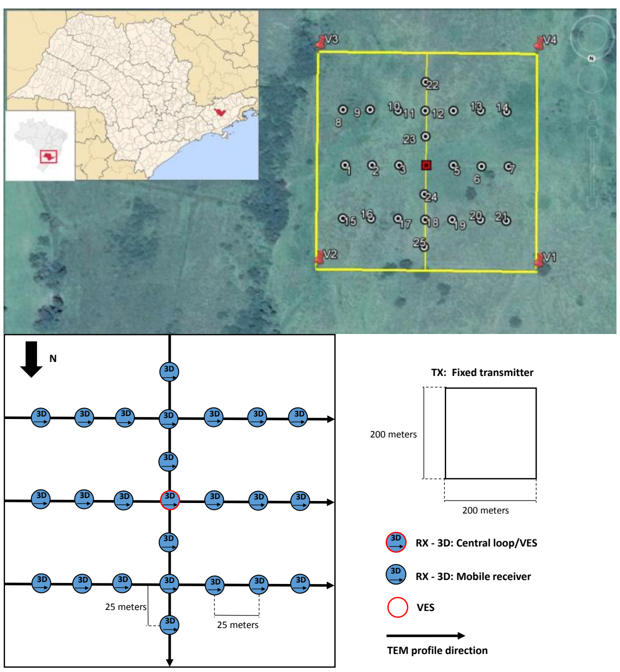

Figure 4: Location of study area and the arrangement used during the campaign.

To VES acquisition data was used Schlumberger array, which had de center of arrangement placed in the center of loop (Figure 4). The Schlumberger scheme used to data acquisition can be seen in the Figure 5.

Preliminary Results

To this paper, only Z component was analyzed for the three available frequencies: 30Hz, 7.5Hz and 3Hz. Figure 6 show the TEM transversal profile shown in Figure 4 (yellow line), where were done 1D individual inversions of each sounding with the intention of to generate a 2D pseudo-section of the profile. This pseudo-section was done using the commercial software IX1D and the inversion used to generate the pseudo-section is called the Occam inversion, which consists of the generation of soft layers (Constable, et al., 1987).

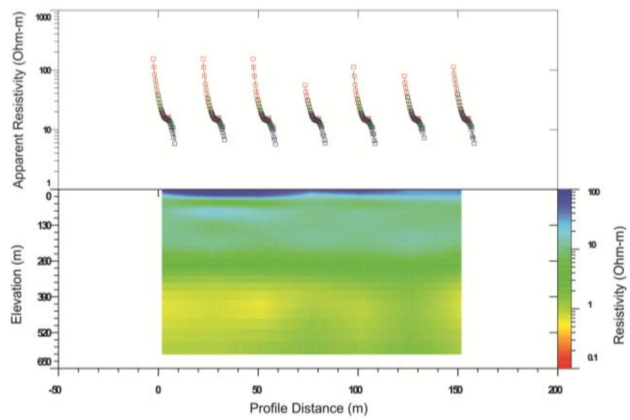

Figure 6: Pseudo-section 2D generated by IX1D software.

In 2D pseudo-section can be note that there is a resistivity decay without to found a more resistivity layer. According to Souza Filho, *et al*. (2012), Taubaté basin has a quite varied granulometry, which consists in sedimentary patches ranging from a more sandy portion until a more clay portion. This information can be corroborated through well information of Brazilian Geological Service (CPRM) (Available in: http://siagasweb.cprm.gov.br/layout/detalhe_poco.php?ponto=3500051142). There is many wells information around the study area, but the nearest well is 780 meters from the study area. This information could be corroborated to resistivity information obtained from TEM/VES inversion.

Figure 7 show the VES individual inversion and the Table 1 show the geoelectrical model. Figure 8 show the TEM individual inversion and the Table 2 show the geoelectrical model.

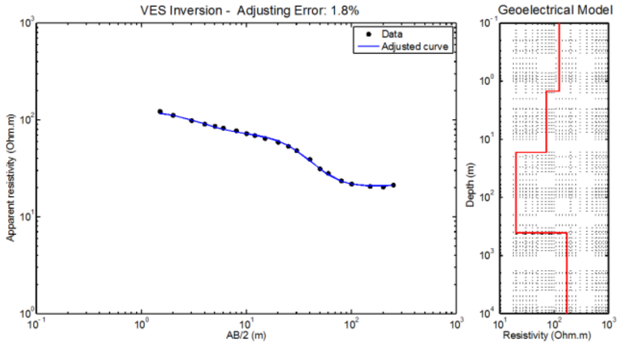

Figure 7: VES 1D individual inversion referring to central sounding.

	Resistivity (Ohm-m)	Thickness (m)	Lithologic type
Layer 1	130,0	1,43	Unsaturated zone
Layer 2	69,9	16,6	Sandy
Layer 3	19,6	188,0	Clayey
Layer 4	27,3	-	unsure

Table 1: VES geoelectrical model.

The well information available by CPRM (Available in: http://siagasweb.cprm.gov.br/layout/detalhe_poco.php?ponto=3500051142) contain a quite variable lithostratigraphy that begins since ~78 meters until 112 meters. According to the resistivity values of Braga (2006), could be compare the resistivity values of the geoelectrical model with the well lithostratigraphy information (CPRM) and conclude that there is an agreement between the information, validating the geoelectrical model for the shallower layers.

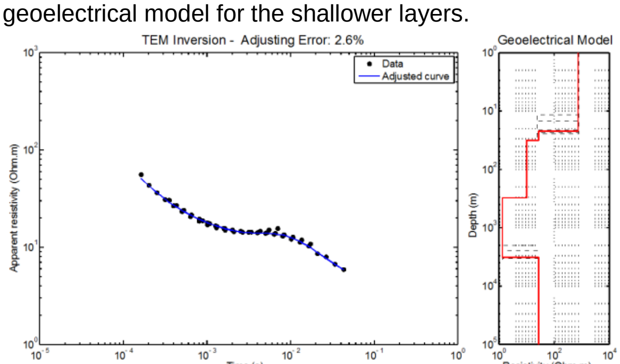

Figure 8: TEM 1D individual inversion referring to central sounding.

	Resistivity (Ohm-m)	Thickness (m)	Lithologic type
Layer 1	62,2	0,9	Sandy
Layer 2	33,9	28,1	Clay-sandy
Layer 3	10,2	262,1	Clayey
Layer 4	1,4	216,7	Clayey
Layer 5	2,4	-	unsure

Table 2: TEM geoelectrical model.

Although TEM has imprecise measures for shallow layer, it could be interpreted by the composition of Taubaté group formation. According to Riccomini (1989), the Resende formation is composed basically by sandstone and sandy mudstone; Tremebé formation is composed basically by argillites, dolomites and sandstones (medium and bulky); and São Paulo formation is composed basically by bulky sandstones, conglomerates, siltstones and laminated argillites and sandstones (medium and thick grading for thin sediments).

Considering resistivity values shown by Braga (2006), this geoelectrical model is considered valid because according to Brazilian Institute of Geography and Statistics IBGE data, the study area contain a porous aquifer with high well productivity and the flow rate of this wells vary between 80-100m³/h (Available in: http://portaldemapas.ibge.gov.br/portal.php#mapa207681).

Figure 9 show the VES/TEM joint inversion and the Table 3 show the geoelectrical model.

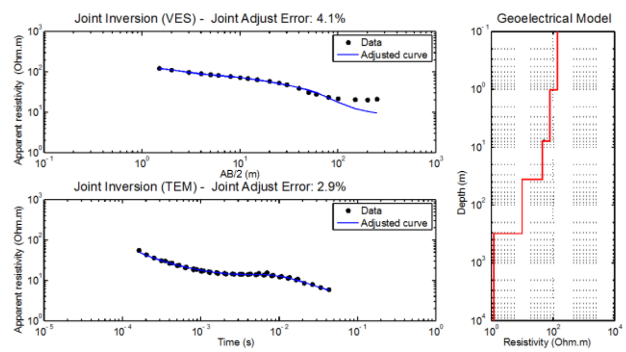

Figure 9: 1D joint inversions of central sounding.

	Resistivity (Ohm-m)	Thickness (m)	Lithologic type
Layer 1	83,3	3,7	Sandstone
Layer 2	67,0	17,5	Sandy
Layer 3	26,8	21,0	Clay-sandy
Layer 4	10,1	258,7	Clayey
Layer 5	1,3	-	unsure

Table 3: Geoelectrical model referring to central sounding.

Table 3 present a geoelectrical model compatible with the individual geoelectrical models of VES and TEM. It is possible to note that resistivity values decreases as the depth is increased and the lithologic type is similar, in dealing with resistivity values, corroborating with 2D pseudo-section.

Besides, 1D joint invertion provides a better geoelectrical model in subsurface reducing the ambiguities in interpretation.

According to Riccomini (1989), fractures zones are present in study area, but in these preliminary results are difficult to identify these zones. However, analyzing 2D pseudo-section, 1D individual and joint inversion, it was possible to identify the shallow sedimentary aquifer around 300 meters of depth and propose an initial geoelectrical model to the study area.

Conclusions

The preliminary results introduced in this paper were useful to present the shallow sedimentary aquifer through a 2D pseudo-section profile created by individual invertions of soundings.
The 1D individual inversion were important to generate TEM/VES 1D joint inversion to validate the interpretation of 2D TEM profile and analyze the decreasing resistivity values in subsurface.
TEM is a very robust tool to a mapping of sedimentary aquifers having a great important to groundwater exploration and when associated to VES technical provides more accurate information.
Therefore 1D joint inversion was very important to reduce the ambiguities of TEM/VES, generating hydrogeological information compatible with study area.

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