TIME-DOMAIN INDUCED POLARIZATION IN THE DETERMINATION OF THE SALT/FRESHWATER INTERFACE (AVEIRO - PORTUGAL)

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Abstract

This paper demonstrates the advantage of 2D resistivity/induced polarization (IP) surveys in the determination of saltwater intrusion in coastal areas. Contrasts of the apparent resistivity and chargeability between saturated freshwater and saturated saltwater zones have been recorded in resistivity and chargeability pseudo-sections. The survey was carried out along two individual lines (GA and PC) 2500 m apart, using a collinear dipole-dipole electrode array. The data were modelled using a 2D inversion program (RES2DINV) and the resultant resistivity and chargeability distributions were then displayed as pseudo-sections. The resistivity and chargeability pseudo-sections define the sedimentary structure of the Aveiro coastal area which, as expected, is similar in both line locations. Therefore, pseudo-sections reveal horizontal layering but also define the dipping salt/freshwater interface in the western part of the sections.

Keywords: salt/freshwater interface; resistivity; chargeability; 2D inversion.

Introduction

The economic, industrial and agricultural development may cause stress on groundwater resources. In coastal regions, the exploitation of large groundwater quantities may lead to saltwater intrusion into freshwater aquifers.

The Aveiro coastal area (Figure 1) shows a severe saltwater intrusion because of the interaction of the Atlantic Ocean, the Aveiro Ria (a large body of saline water) and local freshwater aquifers.

The exploitation and management of the water resources of a coastal region require the knowledge and monitoring of several parameters such as the salt/freshwater interface position, tide effects, hydraulics,

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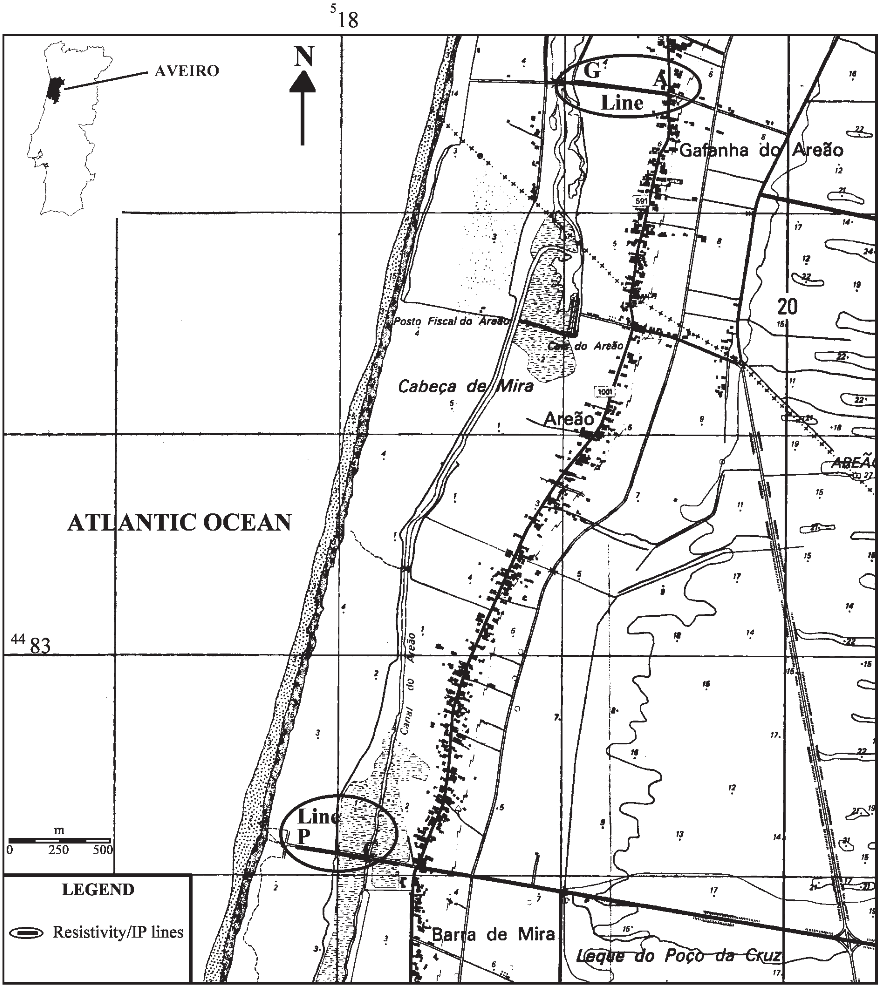

Figure 1. Location of the resistivity/IP survey lines.

water chemistry and geometrical characterization of the aquifers, survey and characterization of the existent withdrawal sites and identification of the contamination points (Senos Matias, 2000). In the Aveiro coastal zone (Figure 1), the above mentioned aspects are important because of the increasing installation of industrial units, agriculture needs and a fast developing tourism, industry that leads to higher consumption of water, and thus an increasing risk of salinization of the shallow Quaternary aquifers.

The geophysical prospecting has been important in the geometric definition of the geological formations, in the determination of position of the salt/freshwater interface, and in the geometric characterization of the resources of the Quaternary aquifers.

In this particular case, electrical methods have been used (Figueiredo and Senos Matias, 1998), as there is a high resistivity contrast between seawater- and freshwater-saturated formations. On the other hand, seawater-saturated formations should give poor induced polarization (IP) response because of the prevailing high ionic conductivity. Thus, it should be possible to discriminate between layers saturated with the two different water types (Sharma, 1997). In fact, the use of IP in groundwater exploration is not new (Vacquier *et al.*, 1957; Bodmer *et al.*, 1968, for example) and IP methods have been used in the study of the seawater/freshwater interface (Roy and Elliot, 1980; Olorunfemi, 1984; Seara and Granda, 1987). However, such investigations used pseudo-sectioning in a qualitative way and one-dimension modelling only.

It must be considered that the seawater/freshwater interface should be modelled as a dipping interface and often there are strong lateral variations in lithology. So this paper takes a two-dimensional approach and modelling to account for those effects.

Regional geology and hydrogeology

The Aveiro coastal area consists mainly of Quaternary sedimentary units composed of alluvium, sand dunes, eolian sands and gravel formations of Pleistocene age, which disconformably overlie older Cretaceous sediments. The upper part of the Cretaceous formations consists of clays and clayey formations, known as Vagos Clays.

The main regional freshwater sources include a shallower unconfined aquifer of Holocene age and a semi-confined aquifer associated with Pleistocene formations of the lower Quaternary (Teixeira and Zbyszewski, 1976; Barbosa, 1981; Marques da Silva, 1990).

The Holocene sediments consist of sands, which overlay levels of organic mud. The composition of the Pleistocene sediments ranges from medium to coarse sand with pebbles. Those freshwater aquifers are recharged by the direct infiltration of surface waters.

Field measurements

Instrumentation

The resistivity/IP time-domain measurements were obtained using the SYSCAL R1 PLUS equipment, operating with the following specifications: pulse duration – 2000 ms; number of stacks – a minimum number 2 and a maximum of 6; standard deviation of the apparent resistivity: $0 < Q < 2$.

However, most of the field measurements were obtained with the minimum number of stacks and a 0 % standard deviation for the apparent resistivity.

Survey design

The measurements were carried out along two individual lines (Figure 1) using a collinear dipole-dipole electrode array. The separation between the lines was 2500 m (Figure 1).

In accordance with the standard nomenclature, the dipole spacing is referred to as "a", whilst the number of "a" spacings between the current and the potential dipole is referred as "n". The "a" spacing used was 10 m and the "n" spacing varied between 1 and 8 for line GA and from 1 and 6 for line PC. The unit electrode spacing was 10 m. Both lines have a general east-west orientation and are perpendicular to the expected dipping seawater freshwater interface.

A total of 441 individual apparent resistivity/IP measurements (276 in line GA and 165 in line PC) were carried out during the course of the survey.

Numerical inversion

The modelling of the resistivity and IP field data used the 2D finite difference inversion program RES2DINV (Loke, 2000). The inversion of the resistivity and IP data sets were done separately. The obtained resistivity model was used for the inversion of the IP data. The inversion was carried out to the point at which the difference between consecutive RMS errors was less than 5 % (RMS error values of below 10 % were regarded as acceptable).

Several IP measurements were found to be negative. These negative values can be a result of poor electrode contacts, that is very high contact resistances, coupling effects between the current and potential circuits or to strong lateral effects and resistivity variations.

At first, the IP modelling procedure included all these values but it was not possible to obtain solutions with RMS errors less than 10 % (figures 2 and 3).

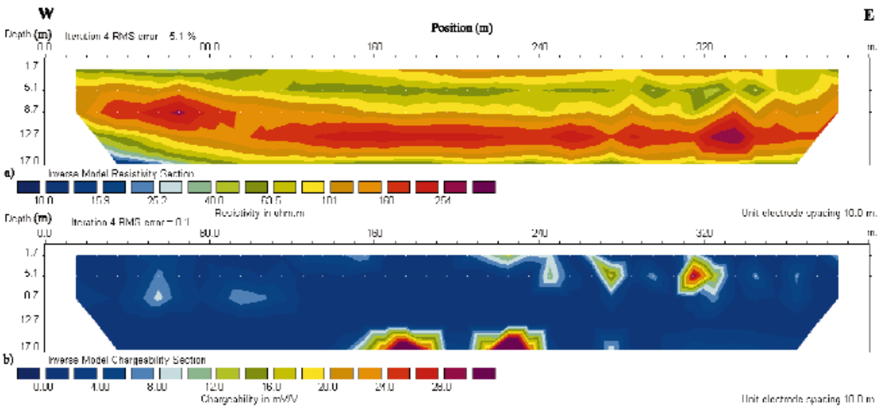

Figure 2. Modelling including negative IP values (line GA): (a) resistivity and (b) chargeability.

Afterwards, it was decided to remove the IP negative measurements, an over-all number of 117 (46 in line GA and 71 in line PC). With this restriction it was possible to model IP data with RMS errors less than 5%. In line GA the IP negative values were more frequent for "n"≥5. In PC there is a random distribution of negative IP values.

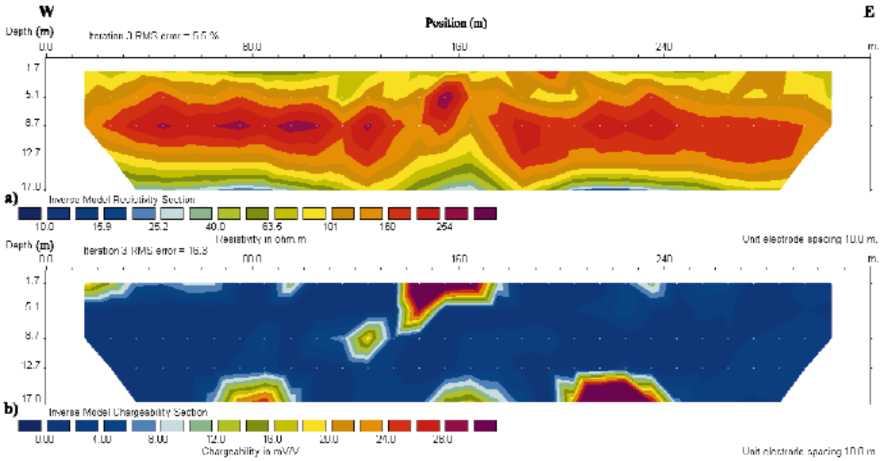

Figure 3. Modelling including negative IP values (line PC): (a) resistivity and (b) chargeability.

Thus, the 2D inversion of the field data resulted in a resistivity and chargeability models consisting of the 167 data points in line GA (1<"n"<6) and 93 data points in line PC. For line GA, a RMS error of 2 % for resistivity and 3.2 % for chargeability was achieved after 5 iterations (figures 4, 5 and 6). For line PC, the models were obtained after 5 iterations with a RMS error of 4.9 % for resistivity and 3.3 % for chargeability (figures 7, 8 and 9).

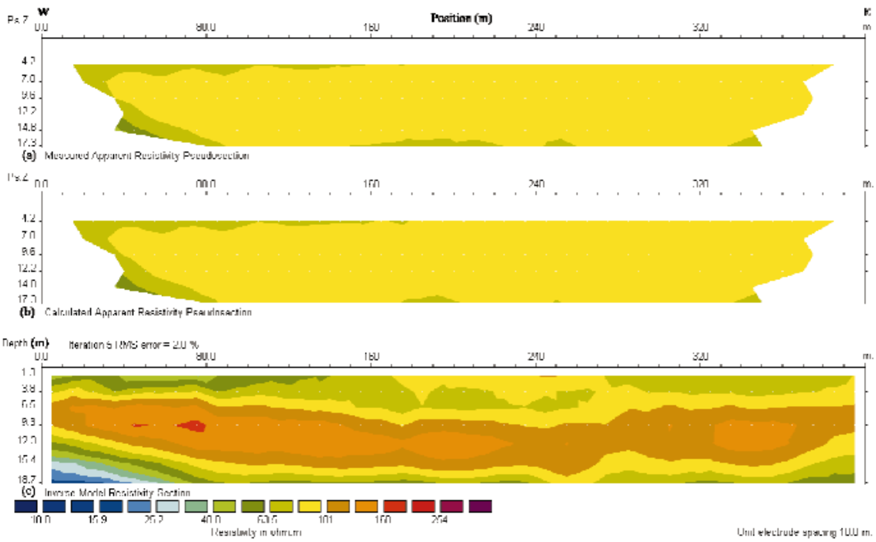

Figure 4. Apparent resistivity pseudo-sections for survey line GA: (a) measured apparent resistivity; (b) calculated apparent resistivity; (c) inverse model resistivity.

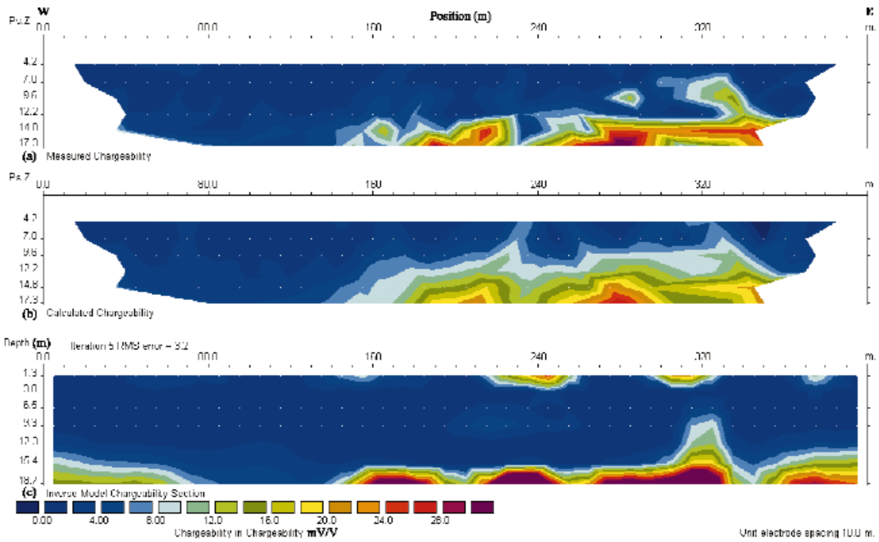

Figure 5. Chargeability pseudo-sections for survey line GA: (a) measured chargeability; (b) calculated chargeability; (c) inverse model chargeability.

Results

The resistivity and chargeability pseudo-sections (figures 6 and 9) are similar for both lines and reveal horizontal layering. The resistivity pseudo-sections show an intermediate geophysical unit of highest resistivity (ρ=130 ohm·m) that corresponds to lower chargeability (M=2 mV/V). This should correspond to a fine sand formation, in accordance with a borehole carried out in the eastern part of line GA. Under this unit, resistivity decreases (ρ=60 ohm·m) with depth, while chargeability increases (M>14 mV/V). Bearing in mind the SJS borehole, (Grangeia, 2001) located in Vagos Dune, to NE of Gafanha do Areão, this unit should correspond to fine muddy sand. In the western end of the both sections, it is visible a salt/freshwater interface showing a clear dipping behaviour and with resistivities lower than 50 ohm·m and chargeability values between 10 and 14 mV/V. In line PC, chargeability section (Figure 9 (b)), the salt/freshwater interface is not apparently visible, which can be due to the poor quality of the chargeability data.

In the resistivity section of the line GA, it is possible to discriminate a shallow unit, with a resistivity of about 80 ohm·m, which correlates well with the sand dune. Underlying this, and with a resistivity of about 100 ohm·m, it can be defined another lens-shaped unit. In the western part of model, at shallower depths, sand dunes show lower resistivity, about 50 ohm·m. In this region, the chargeability pseudo-section shows higher values (M>8 mV/V).

Chargeability measurements were difficult to take and, in general, more iterations are needed if these data are to be inverted. In the GA case, if negative IP values are considered, the dipping character of the sea-fresh water interface is clearly seen on the resistivity sections. However, this feature is not revealed in the IP section (Figure 2 (b)). On the other hand, if negative values are not included in the modelling, the final results show the dipping interface in the IP section as well (Figure 6 (b)).

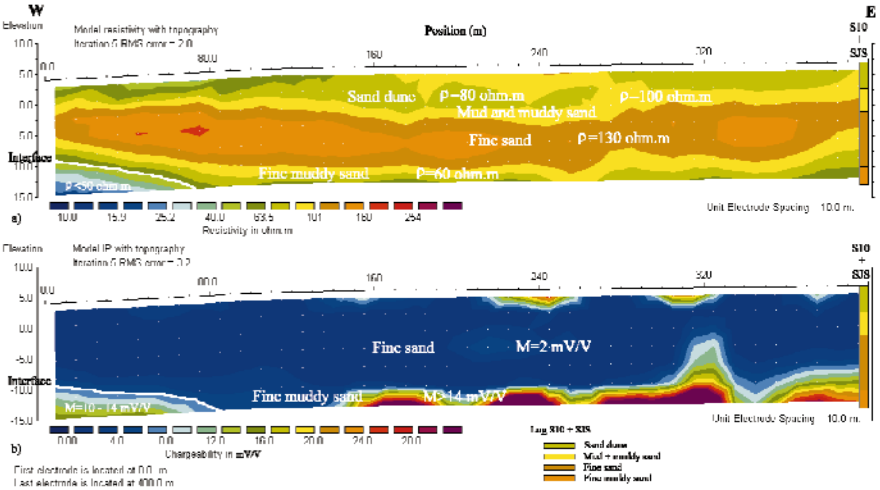

Figure 6. (a) Resistivity and (b) chargeability model sections for survey line GA interpreted in terms of local geology.

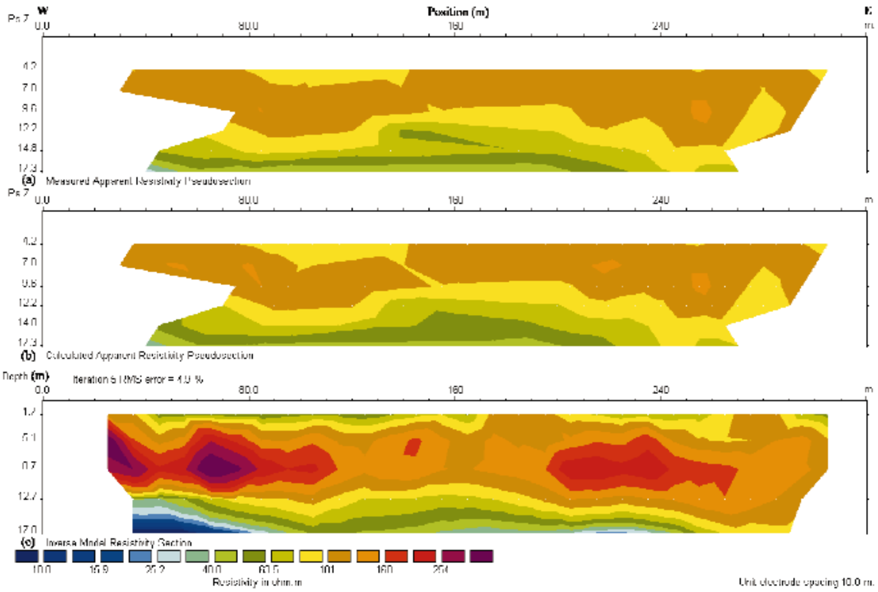

Figure 7. Apparent resistivity pseudo-sections for survey line PC: (a) measured apparent resistivity, (b) calculated apparent resistivity, (c) inverse model resistivity.

Regarding the PC profile, the inclusion of all values, that is, positive and negative IP readings, is found to be an extra difficulty in the modelling, as it is not possible to obtain RMS values for the final model lower than 16.3% (Figure 3 (b)).

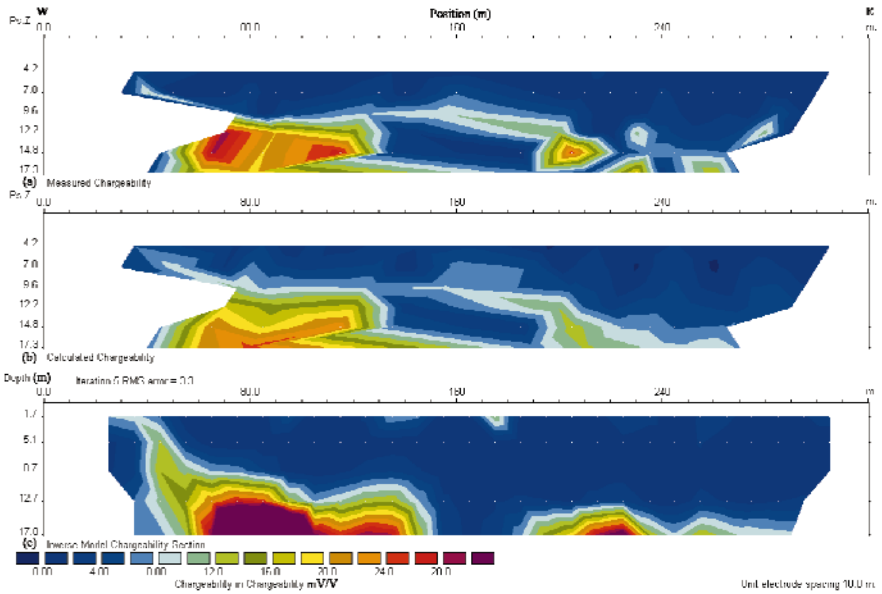

Figure 8. Chargeability pseudo-sections for survey line PC: (a) measured chargeability, (b) calculated chargeability, (c) inverse model chargeability.

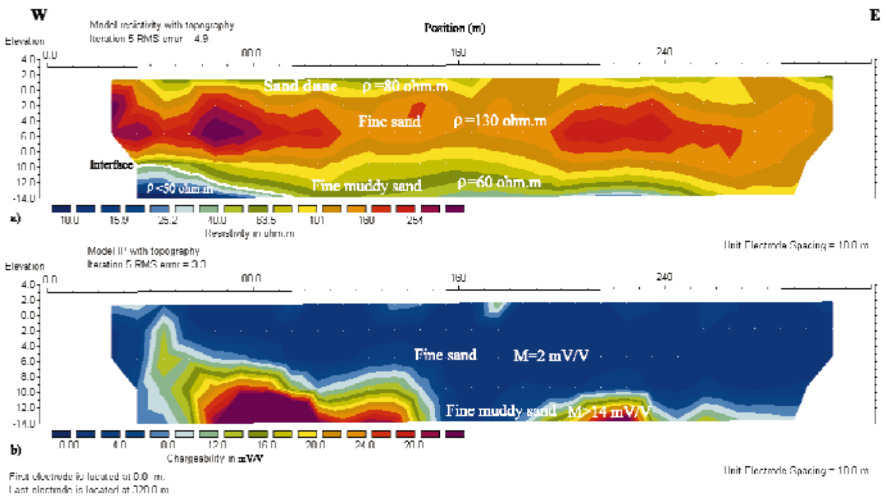

Figure 9. (a) Resistivity and (b) chargeability model sections for survey line PC interpreted in terms of local geology.

Conclusions

The resistivity and chargeability pseudo-sections define the sedimentary structure of the Aveiro coastal area, which is similar in both line locations. As expected, pseudo-sections reveal horizontal layering, but also define a clear dipping salt/freshwater interface in the western part of the sections, showing the 2D behaviour of salt/freshwater interface, and thus proving that simple 1D analysis might not be appropriate.

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