Detection of graves using the micro-resistivity method

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Abstract

This paper describes a case history of the application of resistivity methods on the detection of a tomb tentatively associated with Damião de Goes, a prominent Portuguese humanist who lived in the XVI century. The survey carried out inside Varzea Church comprised dipole-dipole, gradient and pole-pole arrays. The results obtained from the 2D inversion of dipole-dipole data and 3D inversion of the gradient array have shown high resistivity anomalies that were assigned to the walls of the tomb. The low resistivity anomalies observed in between were interpreted as due to the presence of water enriched by ions from the decomposition of human bodies. This result is corroborated by the imaging obtained using the 3D probability tomography of the gradient and pole-pole data. Excavation works, carried out in accordance with the results of the geoelectrical investigation, successfully found a 2.7×0.8×1.7 m tomb, where several human bones have been collected. A 3D resistivity model incorporating the main features of the tomb was built after the excavation. The pole-pole model responses calculated from this model reproduce the main features observed in the data.

Key words *resistivity method – archaeology – 2D modelling – 3D modelling – inversion*

1. Introduction

The case herein presented describes the use of different resistivity arrays to detect the tomb of Damião de Goes, an ancient Portuguese personality. Damião de Goes was the most important Portuguese humanist and died in 1574, spending his life between Portugal, where he was the keeper of Torre do Tombo, and the rest of Europe. In October 2003, a multidisciplinary team proceeded to open the mausoleum of Damião de Goes, in S. Pedro Church, with the purpose of studying the causes of his death. The investigations showed that the bones in the mausoleum corresponded to a set of seven adults and two children and none of the bones was compatible with Damião de Goes (Ferreira, 2003). The skull fracture had a «*post-mortem*» origin, due to the physical and chemical action of chalk and was not the cause of death of the individual. Under these circumstances, it was urgent to find the original tomb of Damião de Goes, proceed with the excavation and try, with the available elements, to investigate the real causes of his death. Recent studies suggested that the Damião de Goes' tomb could be in Varzea Church. The research herein presented is related to the detection of the possible tomb using geophysical methodologies.

A geophysical survey based on the resistivity method was then carried out in that church with the main objective of locating the tomb.

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Resistivity methods have been widely used in archaeological investigations especially in detecting walls and hidden cavities. The interpretation of the data is usually made using the 2D approach, despite the 3D character of some investigated structures. The use of 3D modeling and 3D inversion techniques in archaeology is not common but has been described by some authors (Noel and Xu, 1991; Mauriello *et al.*, 1998; and Cosentino and Martorana, 2002).

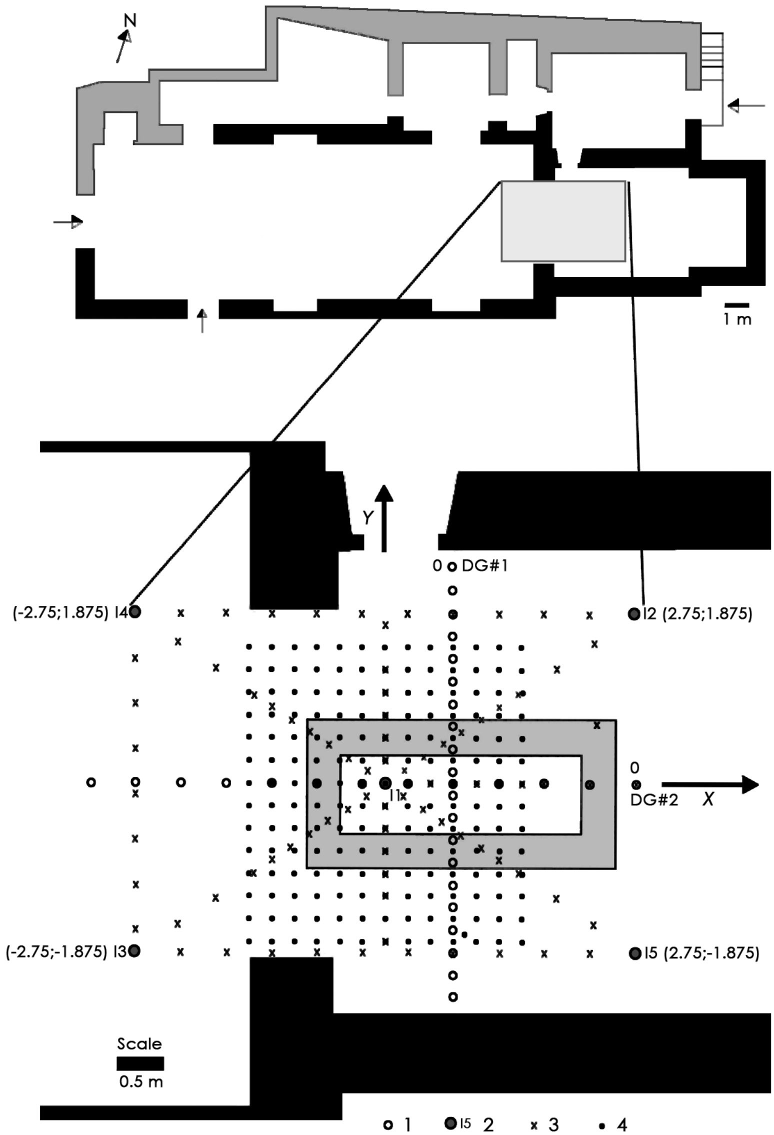

Fig. 1. Inside map of Varzea Church and location of resistivity surveys. 1 – dipole-dipole data; 2 – pole-pole injection; 3 – pole-pole readings; 4 – gradient data.

Even though several authors have presented techniques and optimization procedures to carry out 3D inversions of resistivity data, these have seldom been applied mostly due to the large amount of field measurements and computation capability required. Nonetheless, examples of 3D modelling and inversion of field data can be found in papers recently published (*e.g.*, Zhang *et al.*, 1995; Loke *et al.*, 1996a; Monteiro Santos *et al.,* 1997; Ogilvy *et al.*, 1999; Stoll *et al.*, 2000; Weller *et al.*, 2000).

Recently Mauriello *et al.* (1998) presented a new method to interpret resistivity data, based on the principles of probability tomography proposed by Patella for the interpretation of self-potential measurements in 1997 (Patella, 1997). This method has been applied to archaeological studies (Mauriello *et al.*, 1998; Mauriello and Patella, 1999; Boris *et al.*, 2002) and will be used in this work to jointly interpret the gradient and pole-pole data.

2. Geophysical data

The resistivity surveys took place inside Varzea Church covering an area of 5.5 m×3.75 m (fig. 1). Historical data suggested that the grave would be located along the church in the E-W direction. There were no stones or concrete on the floor of the church, which is made of moisture of sand and clay providing perfect conditions to use resistivity methods in the investigation. Twenty centimetre steel bars (penetrating between 5 and 10 cm in the soil) were used as current electrodes. Non-polarizable electrodes (Pb-PbCl) with a diameter of 7 cm were used as potential electrodes. Three different arrays were used: dipole-dipole, gradient and pole-pole (central radial array). A 600 W square-signal source and a high (1 GΩ) multi-meter for potential measuring were used. The main characteristics of the arrays are described in table I.

Table I. Main characteristics of surveys carried out inside the church. a – potential electrodes spacing.

Array	Characteristics	Length
Dipole-Dipole #1	a=0.25 m	4.75 m; 19 dipoles
Dipole-Dipole #2	a=0.50 m	6 m; 12 dipoles
Gradient	AB=6 m; *MN*=0.25 m	
Pole-Pole	a=0.25 and 0.5 m	

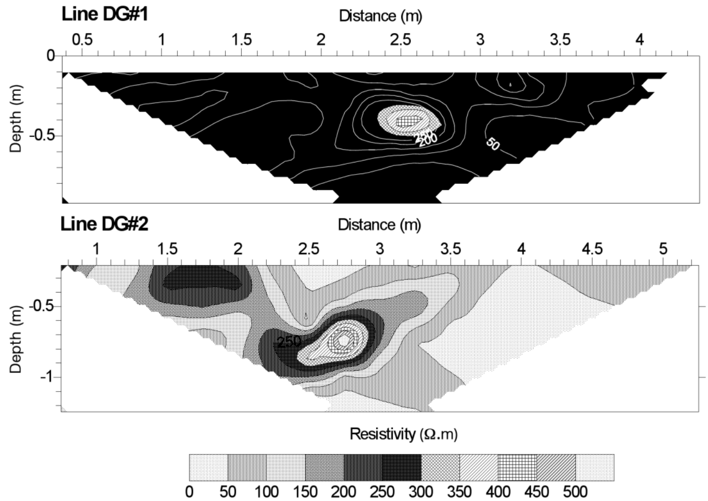

Fig. 2. Apparent resistivity raw data from dipole-dipole survey.

2.1. *Dipole-dipole data*

The dipole-dipole surveys comprised the acquisition of 2 lines perpendicular to each other in order to provide information on the location of the walls of the tomb. The field apparent resistivity pseudo-sections are shown in fig. 2. The dipole-dipole spacing is 25 cm in profile DG#1 and 50 cm in profile DG#2.

The resistive anomalous zones shown in the pseudo-sections might be due to the effect of the walls that are built up with resistive material, probably bricks of loose stones cemented with clay.

2.2. *Gradient data*

The gradient array was carried out with the current electrodes (AB) spaced 6 m. The difference in electrical potential was measured in several parallel profiles using a potential electrode spacing (MN) of 0.25 m. Figure 3 shows the data from the gradient survey. There are three prominent anomalies: a low resistivity area in the middle of the survey and two elongated anomalies with high resistivity located in the borders of the array along the *Y* direction.

In this case the conductive body might be related to the inside part of the tomb and the resistive anomalies with the west and east walls of the tomb, although it seems that they are longer than archaeological information suggested.

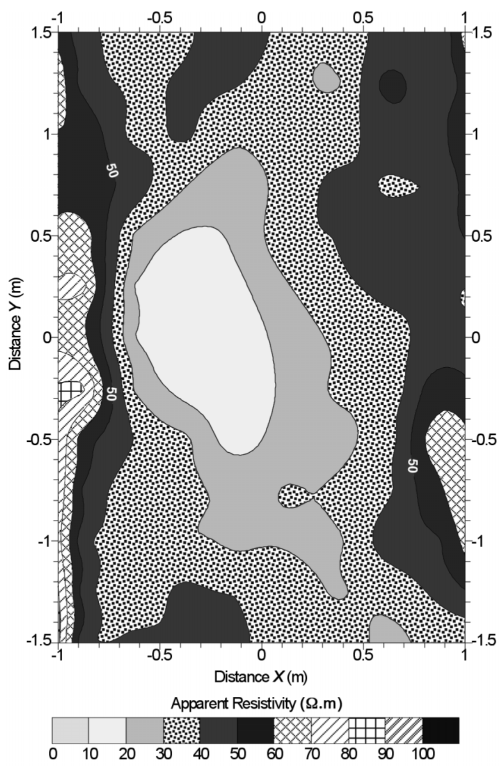

Fig. 3. Apparent resistivity map from the gradient survey.

2.3. *Pole-pole data (radial measurements)*

The pole-pole survey was acquired using a central radial array according to the layout shown in fig. 1. One of current electrodes was located at point I1. The second current electrode was located 15 m away from the centre of the array. The potential measurements were performed using a mobile potential electrode and a permanent one, located at 6 m from the centre of the array. The apparent resistivity map shown in fig. 4 corresponds to the pole-pole survey with the current electrode located at coordinates (0, 0), that is, at point I1 in fig. 1. The more conductive zone crossing the central part of the survey is the principal feature in this map. This low resistivity area might be associated with the filling of the tomb. The more conductive zone around the current electrode correlates very well with the one shown in the gradient apparent resistivity map (fig. 3). The intense apparent resistivity gradient limiting the conductive anomaly marks the presence of the walls of the tomb.

3. Data inversion

3.1. *2D inversion of dipole-dipole data*

The dipole-dipole data were interpreted using a 2D approach in order to determine a preliminary location of the grave and its dimensions. The DG#1 and DG#2 profiles were inverted using RES2DINV software (Locke *et al.*, 1996b). The obtained resistivity models are shown in fig. 5.

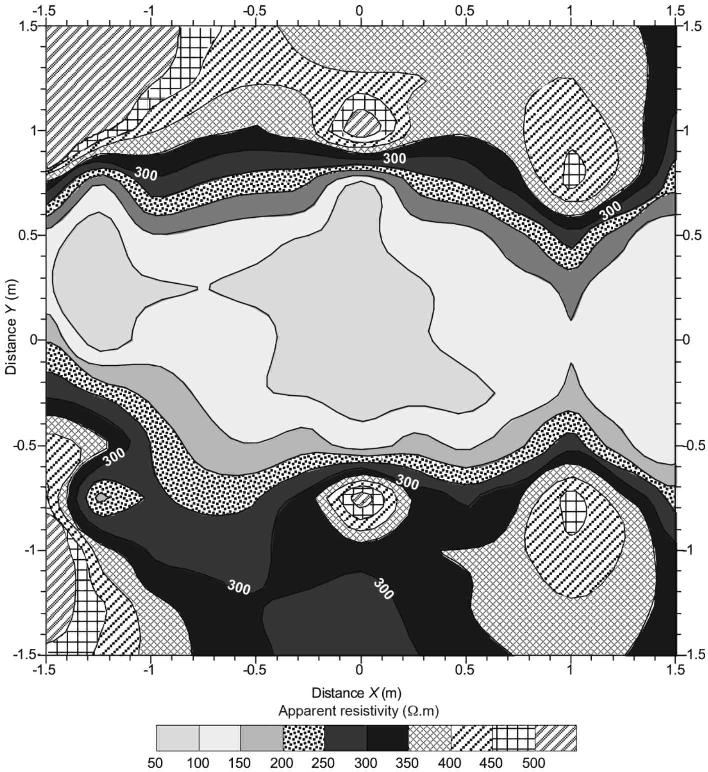

Fig. 4. Apparent resistivity pole-pole data.

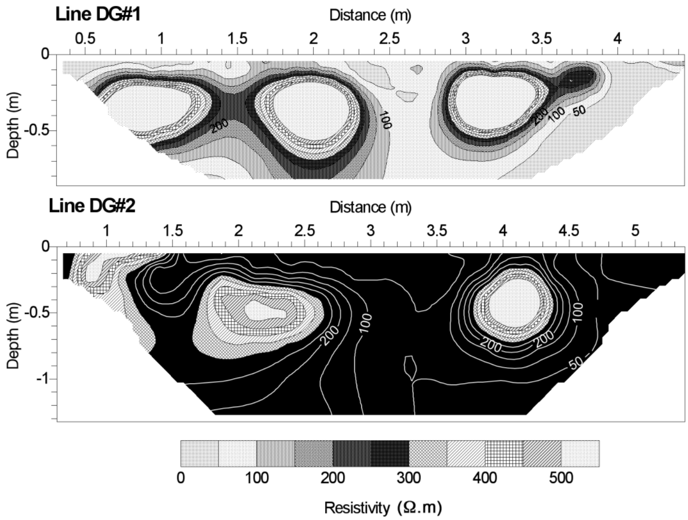

Fig. 5. 2D inverted resistivity models from dipole-dipole surveys.

The misfit between model responses and field data is 12% for line DG#1 and 26% for line DG#2.

Line DG#1 was expected to present the response of the walls that run in the *Y* direction. Indeed two high resistivity anomalies are present in the model, at 2 and 3 m (fig. 5). The model depicts a low resistivity anomaly (~ 50 Ω-m), between those anomalies that are believed to be associated with the soil filling the tomb. This high conductivity of the soil was tentatively interpreted as due to the high content of humidity and also of ions (probably from the decomposition of the human body).

A very similar response was present in line DG#2. Two conspicuous high-resistivity anomalies were found at 2 and 4 m, with a low resistivity anomaly in between. The low resistivity anomaly detected at 5 m is thought to be due to another tomb that was dug in 1941 and later filled with soil.

It was noted that both models showed interesting results and pointed the same location to the grave.

3.2. *3D inversion of gradient data*

The inverse scheme adopted in this paper is based on the one proposed by Sasaki (2001). Basically, the problem is linearized as $\boldsymbol{J}\cdot\Delta\boldsymbol{p}=\Delta\boldsymbol{d}$, where $\Delta\boldsymbol{p}$ is the *M*-vector containing the corrections to the model parameters $\boldsymbol{p}$, $\Delta\boldsymbol{p}$ is the *N*-vector of differences between model responses and measured data, and $\boldsymbol{J}$ is the sensitivity matrix (Jacobian) containing the derivatives of the model responses with respect to the model parameters. In our code those derivatives are calculated using the approach proposed by Locke and Barker (1996a). The vector $\Delta\boldsymbol{p}$ is calculated by minimizing an objective function defined in such a way that smooth constraints on the model structure are imposed (see details in Sasaki, 2001). An iteration procedure is adopted to change the model parameters till the misfit between data and model response is reduced to an acceptable level.

The 3D forward codes used in this study have been developed using finite-element approximations. The basics of such method can be found in Pridmore (1978). In a 3D problem the domain of interest must be discretized into a finite number of elements (hexahedral elements, in this study). The code can accommodate any electrode configuration allowing the use of a great variety of field measurement schemes.

The accuracy of the forward codes depends on several factors, the number of meshes per smallest electrode spacing being the most important of them. A maximum error of 5% can be obtained using four meshes per smallest electrode spacing.

The modeled volume was divided into a mesh of 65×59×23 nodes. The resistivity model shown in fig. 6a) was obtained from the gradient data. The misfit between data and model response is 4.0%. It can be noted that the resistivity contrasts are restricted to the upper part of the terrain (approximately till 1.3 m depth). The model displays a conductive zone in the center of the survey, corresponding to the filled interior of the tomb that is bounded by high resistivity structures which represent the walls. The depth of investigation is strongly limited by the use of a unique AB distance.

3.3. *3D Probability tomography of gradient and pole-pole data*

A joint interpretation of the gradient and pole-pole data was carried out using the probability tomography method proposed by Mauriello *et al.* (1998). According to the authors, this method allows an image reconstruction of the most probable distribution of subsurface resistivity anomalies using the Resistivity Anomaly Occurrence Probability function (RAOP). The RAOP is computed from the Jacobian matrix $\boldsymbol{J}$ and the apparent resistivity anomaly $\Delta\boldsymbol{d}$, assuming a homogeneous and isotropic half-space (Mauriello and Patella, 1999). The RAOP is defined for the jth hexahedral element of the model as

$$\mathrm{RAOP}_j = C_j \sum_{i=1}^{N} \Delta d_i J_{ij} \quad (j=1, 2,\ldots M) \quad (3.1)$$

where $\Delta d_i=\rho^o_{ai}-\rho^c_{ai}$ represents the apparent resistivity anomaly (difference between the observed apparent resistivity and the homogeneous model response at the *i*th measuring point). J_{ij} is the derivative of ρ^c_{ai} for a perturbation of the resistivity in the jth element of the model. C_j is a normalisation factor given by

$$C_j = 1 \Big/ \sqrt{\sum_{i=1}^{N} (\Delta d_i)^2 \sum_{i=1}^{N} (J_{ij})^2}\,. \qquad (3.2)$$

Each RAOP value is interpreted as the probability with which a resistivity increment (RAOP> >0) or decrement (RAOP<0) in the jth element, with respect to a selected reference resistivity can be associated to the whole observed apparent resistivity data set (Mauriello and Patella, 1999).

Figure 6b shows the RAOP slices obtained at different depths from the gradient and pole-pole

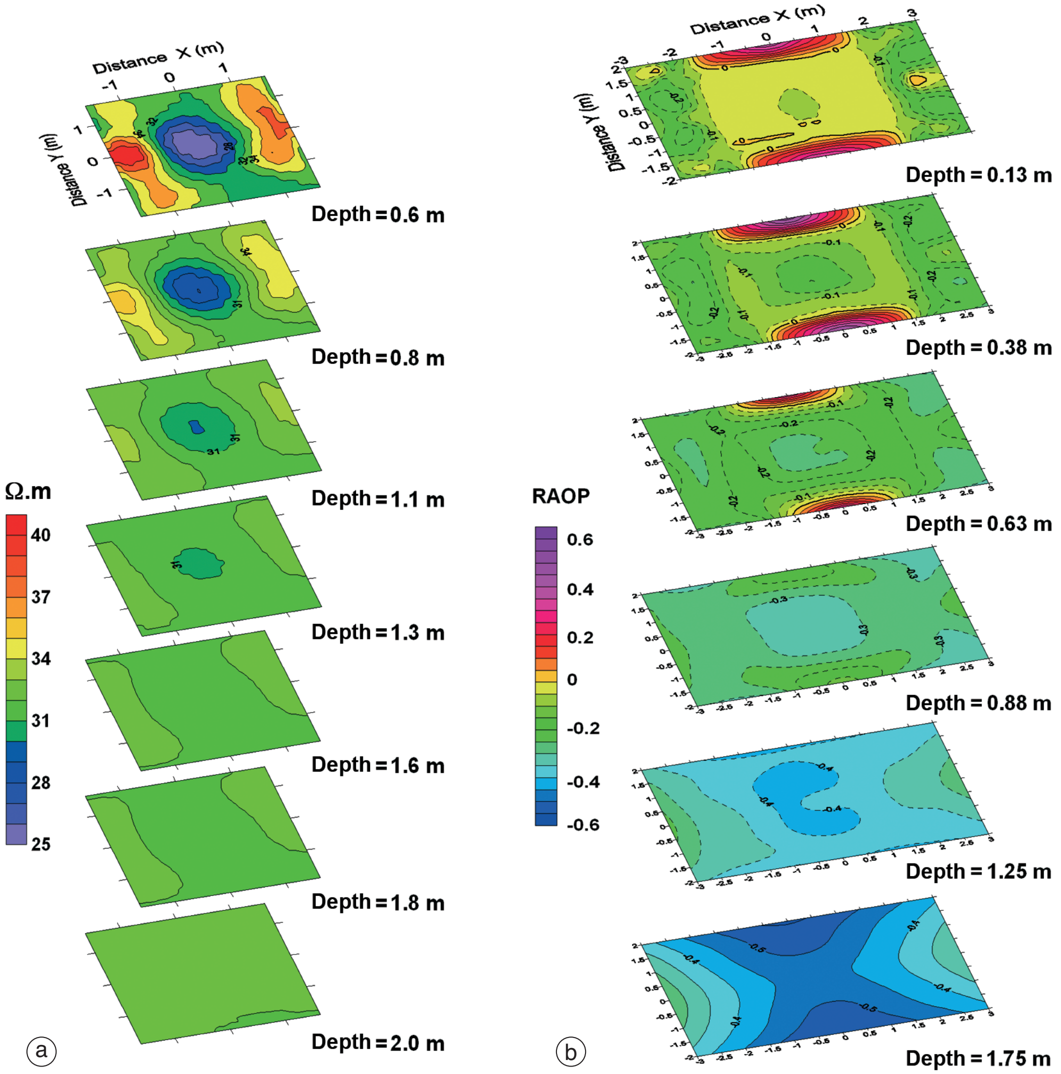

Fig. 6a,b. a) 3D inverse resistivity model obtained from the gradient data; b) sequence of tomographic slices at increasing depth. Dashed contours represent negative RAOP values.

data considering a background resistivity of 200 Ω-m. The RAOP slices display negative values in the central part of the survey that correlated very well with the expected position of the tomb. These negative RAOP values indicate that a conductive body in that zone of the sampled volume is highly probable. The high negative values at depths greater than 1.25 m are mainly associated with the lack of data resolution in depth.

4. Archaeological excavations and results

The excavations were planned according to geophysical results. The tomb was found in the location suggested by the modeling results. Several bones were collected from different parts of the body and are now being investigated by a medical and forensic team. The results showed that the bones are compatible with Damião de Goes' age and height. The tomb dimensions are 2.7×0.8×1.7 m. The walls were 0.3 m thick and are made of bricks of loose stones and a cement of sand and chalk. The tomb was filled with thin soil and clay. Figure 7 shows the tomb after being excavated.

Fig. 7. Photo of the excavation and some of the bones found inside the tomb.

5. *A posteriori* 3D forward modelling

After the end of the excavation a 3D resistivity model including the main geometric features of the tomb was built. The tomb was represented by a homogeneous structure with dimensions of 2.7 × 0.8 × 1.7 m embedded in a uniform medium. The material inside the tomb was modelled as conductive (20 Ω-m) and the walls as highly resistive (1000 Ω-m) materials. The surroundings were modelled as a uniform medium of 200 Ω-m resistivity. The pole-pole model responses have been calculated from this model and are shown in fig. 8a-d. It can be observed that the main features of the data, i) the average apparent resistivity measured within the tomb and ii) the increase in the apparent resistivity values corresponding to the location of the walls of the tomb are well represented in the model responses. However, the very simple model used in this simulation is not able to reproduce the high apparent resistivity values measured in the walls vicinity or the variations observed at points located out of the grove. Because of the roughness of the wall (as can be noted in fig. 7) and the finite dimension of the potential electrodes, the data acquired in the vicinity of the wall might be affected by a more significant error contributing for the large misfit observed in those data. To take into account all those features a much more complex model is necessary.

6. Conclusions

This paper describes the application of micro-resistivity methods in the detection of a

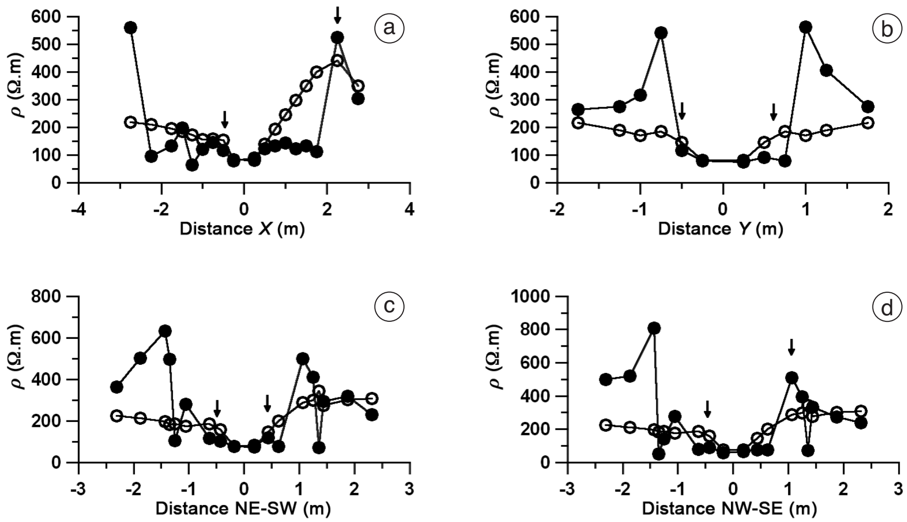

Fig. 8a-d. Forward 3D modelling from the results of the excavation. a) Central profile in *X* direction; b) central profile in *Y* direction; c) The NE-SW profile and d) The NW-SE profile. Data are represented by solid symbols and model response by open symbols. Arrows denote the approximate position of the walls of the tomb.

tomb. The survey carried out inside of Varzea Church comprised dipole-dipole, gradient and pole-pole arrays. The dipole-dipole and gradient data were inverted using 2D and 3D approaches, respectively. A joint interpretation of the gradient and pole-pole data using the probability tomography method was carried out. The results show high resistivity anomalies and high Resistivity Anomaly Occurrence Probability (RAOP) contrasts that were assigned to the presence of the walls of the tomb. The distance between the center of the high resistivity anomalies in both dipole-dipole profiles matches the typical dimensions of the graves from the XVI century. The low resistivity anomalies are detected in between were interpreted as due to the presence of water enriched by ions from the decomposition of human bodies.

Excavation works, carried out in accordance with the results of the geoelectrical investigation, successfully found a 2.7×0.8×1.7 m tomb, where several human bones have been collected. Pole-pole responses, calculated from an *a posteriori* 3D resistivity model incorporating only the walls of the tomb compared quite favourably with the acquired data. However a more detailed modelling, which will include all the acquired data, will be presented in a future paper.

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