Electrical methods in archaeological exploration

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Abstract - Nowadays there is no doubt that Geophysics, and in particular resistivity methods, provide powerful tools to help archaeologists in excavation planning. Although more time consuming, these methods can be used in areas with strong cultural noise, where magnetics cannot be used, and when some frequencies are forbidden and therefore restrictions on the use of ground probing radar and EM exist. High resolution 2D and 3D resistivity methods are now possible and faster because of field equipment development, and techniques, as well as the introduction of fast and reliable numerical methods to carry out interpretation and modelling. Herein, an account of the different arrays, a discussion on the noise measurements, on resistivity profiling, mapping and imaging is given. Finally, an older, but fast and reliable modelling technique is revisited, and its use on worksheets and laptop computers provides an alternative and efficient way for a quick modelling of field data.

1. Introduction

Traditionally, archaeological exploration consists in careful trenching and coring in sites having historical or traditional documentation, surface artefacts, or morphology suggesting earlier human occupation. Then, the excavated material is analysed in a suitable laboratory and a 3D relationship among the remains is proposed on the basis of an accurate field recording carried out as the exploration works progress. However, this approach has been changing towards the use of laboratory instrumentation to analyse relevant materials and to evaluate sites of interest before land development projects start. Therefore, the time and the effort required to excavate entire areas are sometimes a luxury that archaeologists cannot afford. Furthermore, if there is no surface evidence to guide the archaeologist, the time intensive nature of trenching usually prevents any relevant fieldwork beyond the stages of a random shallow search.

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On the other hand, the slow process of trenching exposes previously preserved remains to weathering, vandalism, etc, and the excavation process itself destroys the space relationships of the artefacts. Thus archaeologists have always wanted fast, efficient, non-destructive and reliable reconnaissance methods.

The growing pressure by developers, as well as public opinion, who are more and more concerned with the preservation of historic and prehistoric artefacts and sites, calls for an urgent, if not desperate, need to propose high resolution, fast and non-destructive methods to evaluate the hidden dimensions of concealed archaeological remains in areas of interest.

Fig. 1 shows the relations between the number of boreholes and the probability of detection of a target with an area of 10% the total area to investigate.

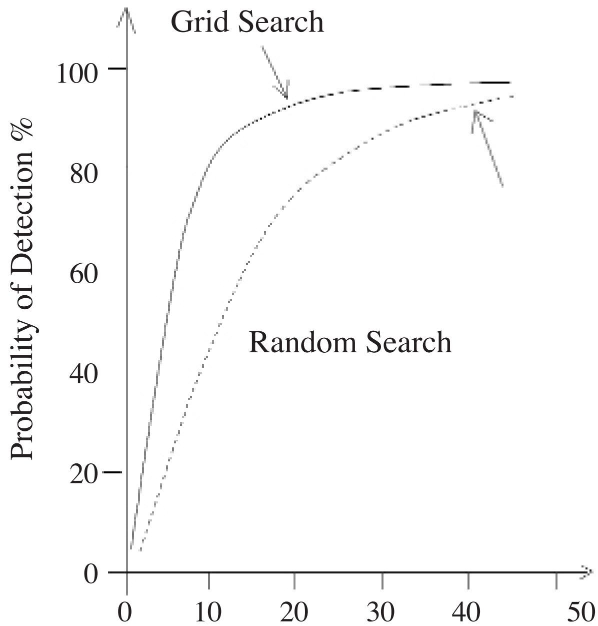


Fig. 1 - Probability of detection vs number of boreholes (target area 10% of the total area to investigate (after Benson et al., 1982).

As can be seen, the efforts of a random search are not as rewarding as those for a grid search. However, if the probability curve can be further shifted to the left of the grid search probability curve, time and effort can be saved in archaeological excavations. Thus, alternative techniques such as Geophysics have been used to aid excavation planning.

As a matter of fact, geophysical methods provide the rapid, non-destructive exploration techniques that archaeologists need. In addition, as these methods allow a fast and uniform reconnaissance of an entire site and an overall view of the space relationships within a large area is not difficult to obtain.

Geophysical methods have been used in archaeological exploration since the 1940's, or even earlier if aerial photography of archaeological sites is included, and the full range of methods has been used in the investigation of archaeological sites, perhaps with the sole exclusion of borehole techniques.

The need for higher resolution led to the quick development of methods and to the introduction of new techniques, such as the ground probing radar in the 1970's, as well as more accurate equipment as, for example, high sensitive magnetometers.

However, in areas where cultural noise is high, such as urban areas, or when there are limitations on the frequency of the signals to be used, conventional resistivity methods can still be of paramount importance in archaeological exploration. These methods have been further refined and the use of complex multicable systems and field laptop computers allow the fast mapping of considerable areas in 2D and 3D modes.

The use of resistivity methods in archaeological exploration precedes the use of other methods (Wynn, 1986). They were first used in the 1940's in England (Atkinson, 1952; Aitken, 1974), and allow to distinguish stone foundations and remains, that are more resistive, buried ditches, more conductive, as well as cavities, whose behaviour depends on the material they host.

2. Basic concepts and arrays

If a current electrode A (Fig. 2) is on the surface of an homogeneous isotropic half space of resistivity, the electrical potential at a point M, on the surface of the same medium and at a distance r from A is given by:

$$V = \frac{\rho I}{2\pi r} = \Phi\,(r).$$

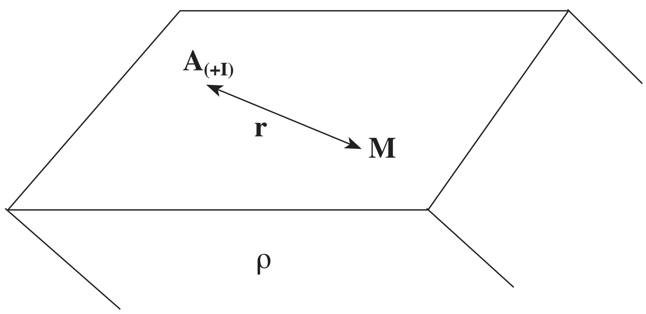


Fig. 2 - The two electrode array.

Generally speaking, four electrode arrays are used (Fig. 3) that is two current electrodes A, B and two potential electrodes M, N.

In this case, using electrical potential theory, the measured potential difference between electrodes M and N is given by:

$$V = \Phi\,(r_1) + \Phi\,(r_2) + \Phi\,(r_3) + \Phi\,(r_4). \qquad (1)$$

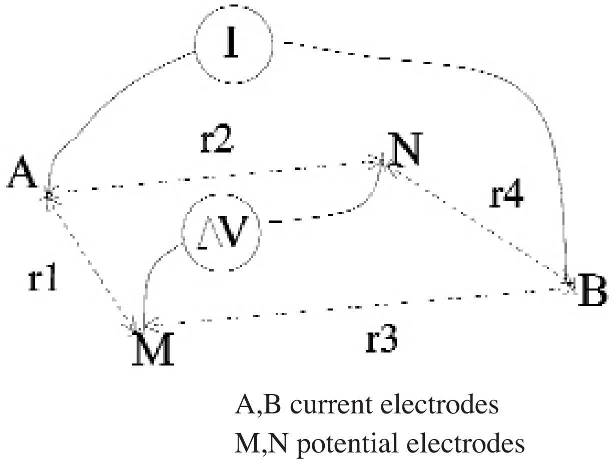


Fig. 3 - General four electrode array.

When conducting geophysical surveys in archaeological exploration it must be kept in mind that a uniform coverage of the survey area is needed. Thus, the first step in field operations is the gridding of the total area to investigate. Any electrode arrangement should take advantage of the gridding already done. Therefore, not all the electrode configurations used in resistivity methods should be considered if field operations are to be optimised.

Generally two dimensional grids, most of the time square or rectangular ones, are considered and this imposes a practical limitation to the array to be used. That is, in accordance with their geometry the Wenner, Square, Dipole Dipole, Tri electrode and the more recently proposed (Baker et al., 2001) Baker L-Shape arrays (Fig. 4) are favoured.

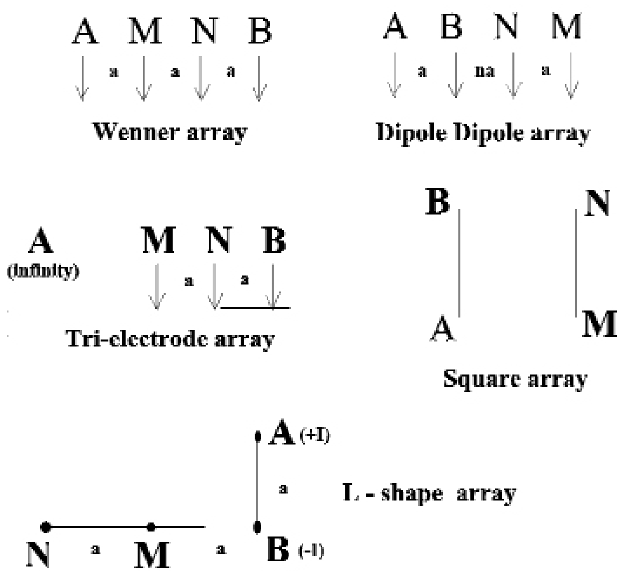


Fig. 4 - Four electrode arrays used in archaelogical exploration.

These arrays have been used extensively in mineral exploration and in other applications, but it must be remembered that in archaeological exploration the geophysicist is looking for lateral changes and inhomogeneities in the surface resistivity distribution instead of the more common layer stratification problem. Thus, these arrays, or better, their use has to be adapted and further parameters, not only the apparent resistivity, should be considered to enhance their resolution and detection capabilities.

Therefore, the use of tripotential methods and of the square array can eventually show some advantages as they provide further information to aid in the diagnosis of archaeological structures of interest.

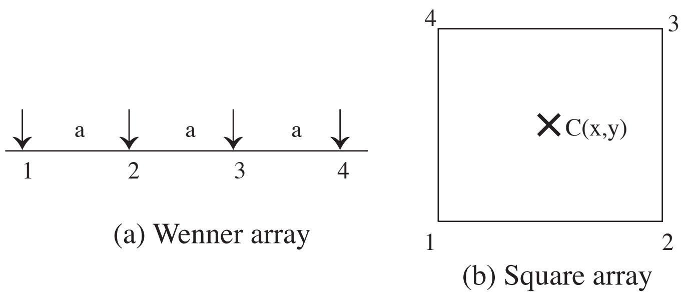
3. Tripotential methods

Tripotential methods were introduced by Carpenter and Habberjam (1956). These consist of three Earth resistance measurements as shown in Fig. 5a for the Wenner array and Fig. 5b for the square array.

Its use allows a check on the field data quality as well as on the calculation of the ratio between the resistivities β and γ, an aid to assist in the diagnosis of concealed structures (Acword and Griffiths, 1985).

4. Square array

Based on tripotential techniques the square array of electrodes (Fig. 5b) was proposed (Habberjam and Watkins, 1967).



Configuration	Electrode			
	1	2	3	4
α	A	M	N	B
β	A	B	N	M
γ	A	M	B	N

Fig. 5 - Tripotential measurements for the (a) Wenner array and for the (b) square array.

Habberjam (1975, 1979) has given an extensive analysis of the square array's merits and drawbacks, both for mapping and for sounding. An advantage of the square array is that two apparent resistivity values can be measured in mutually perpendicular orientations. Therefore, the average of the two measurements provides a more orientationally stable measurement of apparent resistivity. Moreover, the square array has the ability to reveal the existence of lateral effects by the observed difference between the two mentioned measurements. Thus, the orientational effects, arising from lateral inhomogeneities existing in the ground can be expressed in terms of the so-called Azimuthal Inhomogeneity Ratio (AIR), given by:

$$AIR = 2x \frac{R\alpha - R\beta}{R\alpha + R\beta} = 2x \frac{R\gamma}{R\alpha + R\beta} \ . \qquad (2)$$

The square array is very convenient for use in archaeological exploration, once previous gridding of the area is done.

5. Field techniques

The commonest field resistivity techniques in archaeological exploration are profiling, mapping and imaging. The use of resistivity soundings is not very common because, in general, resistivity methods in archaeology look for lateral changes and not for layering associated with vertical changes of layering. Nevertheless, if layering is the aim only small depths of investigations are looked for, as well as, a very good resolution. So, as a good definition of a resistivity sounding curve needs at least three or four sampling points per decade, this might be difficult to accomplish in the measurements for the first decades because of the needed dimensions.

5.1. Resistivity profiling

In this case, the chosen array is moved from position to position over a previously defined line. Line orientation should be perpendicular to the expected remains strike.

However, the geometry of the array used might introduce some noise in field measurements as can be seen in Fig. 6.

Some lower amplitude resistive anomalies occur and can make interpretation more difficult. Moreover, if several interfaces or dykes are present, these low amplitude anomalies can add up and produce important noise, disturbing interpretation and introducing false anomalies.

5.2. Resistivity mapping

When several profiles are carried out, a resistivity map can be produced by plotting the resistivity measurements in accordance with their (x,y) positions. Mapping does not necessarily need the previous knowledge of the remains strike.

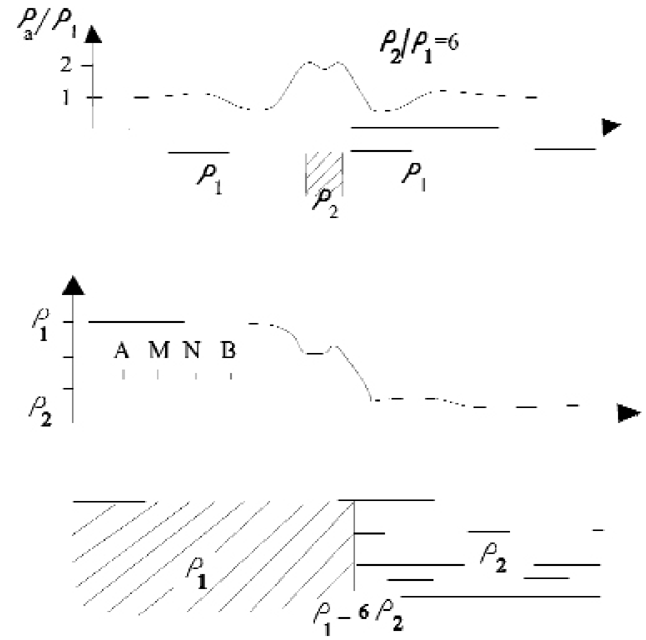


Fig. 6 - Resisitivity profile over (a) an outcropping dyke and (b) an outcropping vertical interface.

5.3. Imaging

No doubt this is the most powerful technique, although the most expensive. Imaging can be carried out in accordance with Loke procedures (Loke and Barker, 1996a, 1996b) or by conducting some small resistivity soundings from position to position on a chosen profile. In this case, if the Wenner array is used "soundings" can be performed with "a" spacings of 0.25, 0 .50, 0.75, 1.0, 1.5 and 2 metres for instance. Then, the apparent measured resistivities are plotted in accordance with their position and "a" value used on the imaging profile. Thus, an image of the behaviour of the resistivity distribution with depth can be obtained. If several profiles of soundings are carried out several images are obtained and a 3D picture of the ground will be available. The recent development of 2D and 3D interpretation material allows a faster and more convenient way for the interpretation of these data.

However, field 2D and 3D work can still be time consuming if proper multicables, computers and appropriate software are not available.

6. Geological noise

Besides the previously mentioned noise, originated from the geometry of the used array of electrodes, the use of resistivity methods in archaeology must take into consideration noise from a geological origin. As a matter of fact geological 2D features can give similar anomalies to those arising from the distribution of archaeological remains and thus can blur the interpretation or give misleading results.

In Fig. 7, a resistivity profile, carried out near the tower of “Centum Cellae” (Belmonte, central Portugal) is shown, as well as the local geology. It is easily seen that the promising anomalies are no more than responses to local near surface geological features.

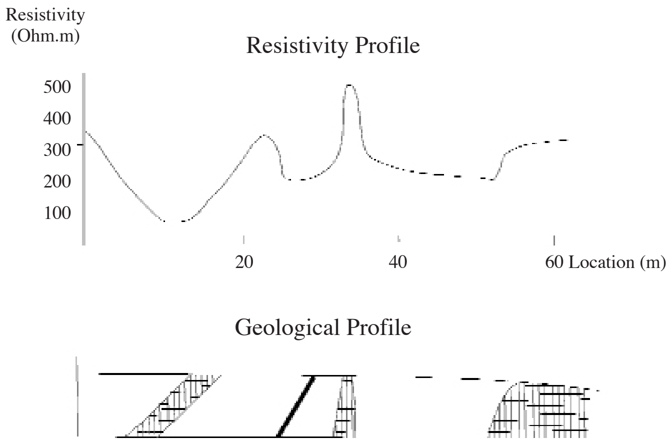


Fig. 7 - Resistivity profile near “Centum Cellae” (Belmonte central Portugal).

7. “Villa Cardilio” profiling (Wenner array)

Villa Cardilio is a Roman settlement near Torres Novas, central Portugal. The application of geophysical methods in this area included both resistivity and magnetic exploration (Monteiro and Senos Matias, 1987). A resistivity profile carried out in the vicinity of the known remains is shown in Fig. 8

The data were obtained using the Wenner array, with an “a” value of 1 m and spacing interval of 1 m.

The resistivity profile clearly shows the anomalies m_1, m_2 and m_3 that, after excavations were shown to correspond to buried walls at depths less than one metre. It must be pointed out

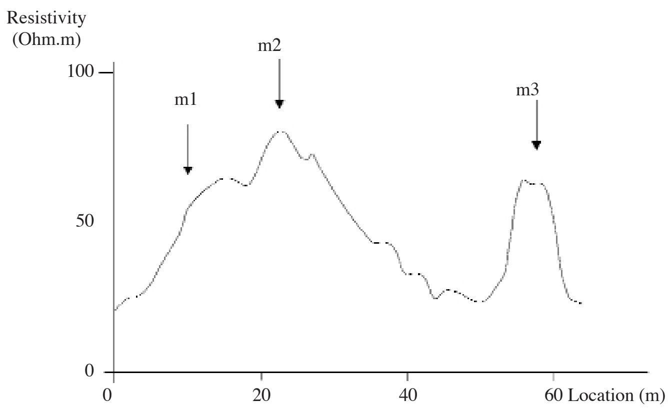


Fig. 8 - Resistivity profile in Villa Cardilio.

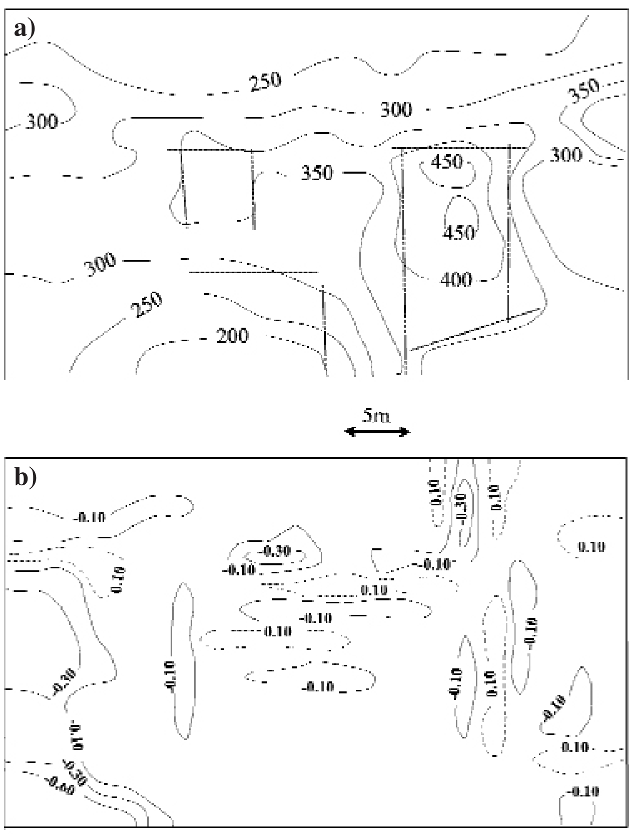
that the area between anomalies m_1 and m_2 corresponds to the accumulation of stones and other archaeological remains which should be responsible for the high resistivity values recorded between m_1 and m_2.

8. "Ferrol" mapping (square array)

A comprehensive geophysical survey was carried out near Mugardos, Ferrol (Spain) to investigate an area where the existence of buried Roman ruins was suspected (Senos Matias and Almeida, 1992). Square array mapping was done with a square side of 2 metres over a 2x2 metre grid. Once the grid was set on the ground it was very easy to conduct the square array survey and special multicables as well as field control devices to interchange the current and potential electrodes, were used.

The apparent mean resistivity and the AIR maps of the area are shown in Fig. 9. Both maps show orthogonal patterns clearly, in approximatly north-south and east-west alignments.

The square array was oriented so that the electrodes 1,4 (Fig. 5b) are parallel to the width of the rectangle which corresponds to the north-south direction.



---- Positive AIR values —— Negative AIR values

Fig. 9 - (a) Mean apparent resistivity and (b) AIR maps.

In the AIR map (Fig. 9b), north-south alignments are parallel to the square orientation and their pattern includes a zone with negative AIR values north-south oriented and positive AIR values on both sides of that negative anomaly. Bearing in mind the response of the AIR over 2D models (Habberjam, 1979), the structure responsible for such an anomaly must be located over the negative anomalies. On the other hand, east-west alignments are perpendicular to the square orientation and they include positive AIR values bounded by negative AIR values. Again, based on the behaviour of the AIR over 2D structures (Habberjam, 1979), in this case the structure should be located over the positive anomalies.

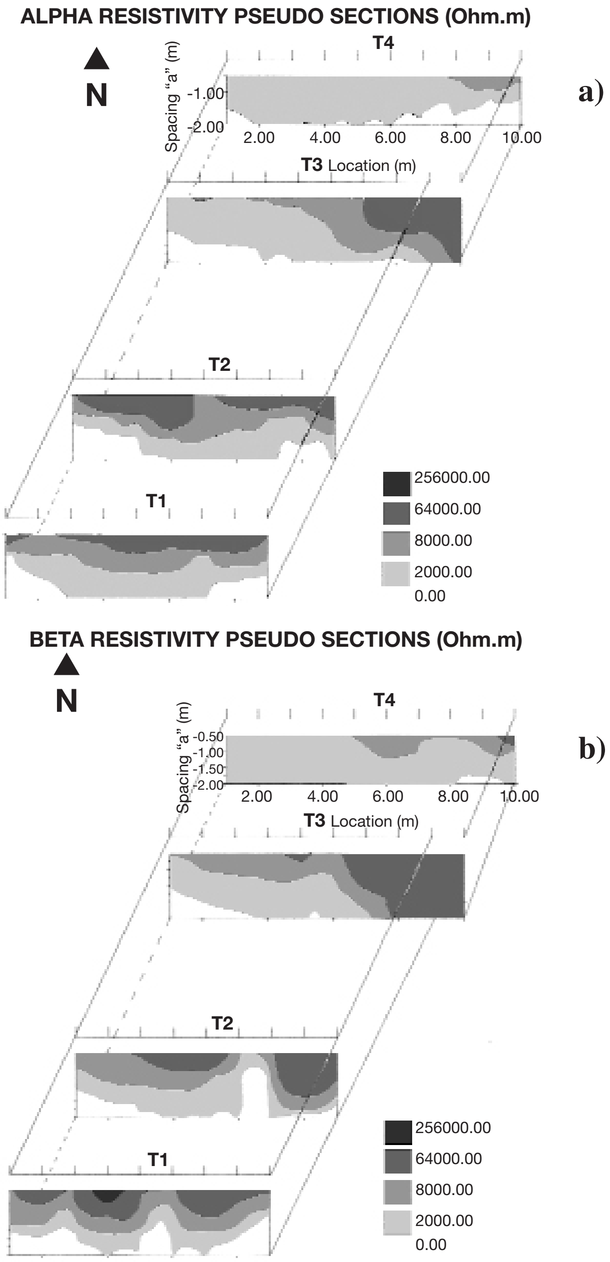


Fig. 10 - 3D Resistivity study inside the "Casa do Infante"; (a) Wenner alpha and (b) Wenner beta or dipole-dipole.

Fig. 9a also shows, in dashed lines, the results of the archaeological excavations and, as can be seen, the overall results are in very good agreement with Geophysics.

9. "Casa do Infante" 3D study (Alpha and Beta Wenner array)

The use of 2D and 3D geophysical imaging may be time consuming but it is also rewarding. A 3D resistivity study was carried out inside the "Casa do Infante" , Porto, North Portugal, to investigate medieval structures (Senos Matias et al., 1995). The Wenner tripotential technique was used and thus results will be presented in terms of Wenner alpha and Wenner beta, which is a dipole-dipole. The resistivity results are shown in Fig. 10.

The Wenner array tripotential data were obtained using an "a" spacing of 0.5, 0.75, 1, 1.5, 2 and 2.5 m and the distance between adjacent soundings was 1 m. The pseudo sections for Wenner alpha and beta (that is dipole – dipole) were then constructed by plotting each reading in accordance with its spacing and sounding location centre.

As can be seen and expected, Wenner beta pseudo sections show a better lateral resolution and several resistive anomalies can be defined. These anomalies were later confirmed as buried walls and pavements, in Fig. 11. Furthermore, from the behaviour of the contouring lines it is also possible to define the attitude and position of the bedrock (Fig. 11).

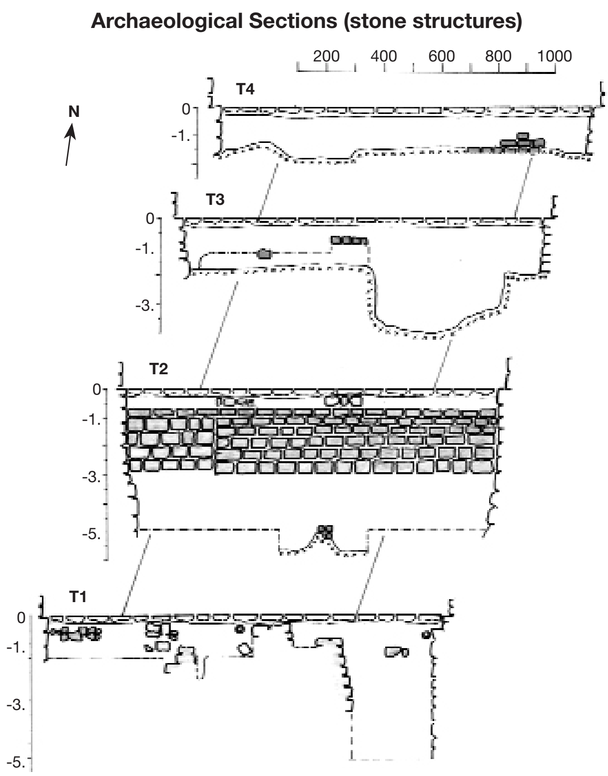


Fig. 11 - Archaeological excavations at "Casa do Infante".

10. Composition of 2D anomalies

In the last few years, some powerful algorithms have been proposed to obtain resistivity responses over 2D models (Loke and Barker, 1996a, 1996b). However, some simple modelling can be obtained from the composition of 2D models for which the theoretical resolution is easily available. Thus, Habberjam and Jackson (1974) proposed the so-called composition rules. Briefly, two models each theoretically embracing a half space can be combined to produce another half space model. There are two composition rules, the first applies to outcropping models and the second applies to concealed models.

10.1. First rule

Having elementary distributions, such as the outcropping vertical interfaces (a) and (b) of Fig. 12, $\rho\ (x,z)_1$ and $\rho\ (x,z)_2$ they can be combined to obtain a simple dyke (c), to the right of Fig. 12.

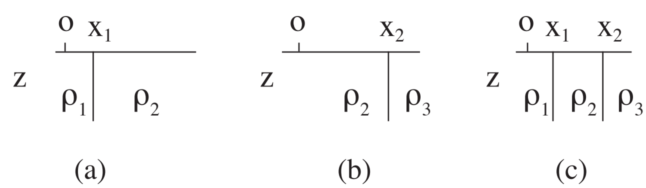


Fig. 12 - Composition of outcropping models.

The single vertical interface model has a simple solution based on image theory (Van Nostrand and Cook, 1966) and the first composition rule allows:

1. to normalize both spaces (a) and (b) with respect to ρ_1 and ρ_2 thus

$$\rho\ (x,y)_1 / \rho_1\ (= 1 \text{ for } x < x_1) \text{ and } (= \rho_2 / \rho_1 \text{ for } x > x_1), \tag{3}$$

and

$$\rho\ (x,y)_2 / \rho_2\ (= 1 \text{ for } x < x_2) \text{ and } (= \rho_3 / \rho_2 \text{ for } x > x_2); \tag{4}$$

2. now these two distributions are multiplied, and their product is the distribution $M\ (x,z)$ that is:

$$M\ (x,z) = (\rho\ (x,z)_1 / \rho_1)\ x\ (\rho\ (x,z)_2 / \rho_2) \tag{5}$$

and

$$\begin{aligned} &= 1 \text{ for } x < x_1 \\ &= \rho_2 / \rho_1 \text{ for } x_1 < x < x_2 \\ &= \rho_3 / \rho_2 \text{ for } x > x_2; \end{aligned} \tag{6}$$

3. finally the combined section can be obtained by multiplying $M(x,z)$ by ρ_1 to obtain the model to the right of Fig. 13,

$$\rho\,(x,z)_c = \rho_1\, M\,(x,z). \quad (7)$$

Thus, the first composition rule can be summarized as follows:

$$\rho\,(x,a)_c = \rho_1\, M\,(x,a) = \rho_1\,(\rho\,(x,a)_1 / \rho_1\, x\,(\rho\,(x,a)_2 / \rho_2)). \quad (8)$$

10.2. Second rule

This rule applies to concealed models, such as the ones in Fig. 13.

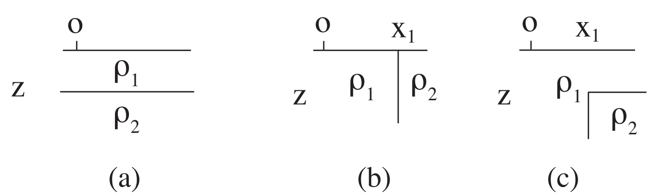


Fig. 13 - Composition of concealed models.

The second composition rule is applied as follows:
1. normalize the two elementary spaces (a) and (b) in Fig. 13 with respect to ρ_1;
2. subtract 1 from both spaces;
3. renormalize both spaces by multiplying them by $\rho_1 / (\rho_2 - \rho_1)$, or divide by $(\rho_2 - \rho_1) / \rho_1$;
4. multiply the two modified elementary spaces to obtain the space $P(x,z)$;
5. finally invert operations 3, 2 and 1.

The two rules can be combined together to obtain more complex models (Habberjam and Jackson, 1974; Senos Matias and Habberjam, 1984).

As an example, these simple rules are going to be used to obtain the solution for a concealed tunnel (Fig. 15). To obtain such a model the procedure starts with a simple three-layer Earth model (a) and an outcropping vertical dyke (b), at the top of Fig. 14.

Thus a more complex model is easily obtained if the theoretical model solutions for the simpler models are introduced and worked out on a worksheet. More models of archaeological significance, such as, pavements, concealed walls, etc, can be modelled easily. Hence, this procedure is a fast and simple alternative to the complex numerical modelling.

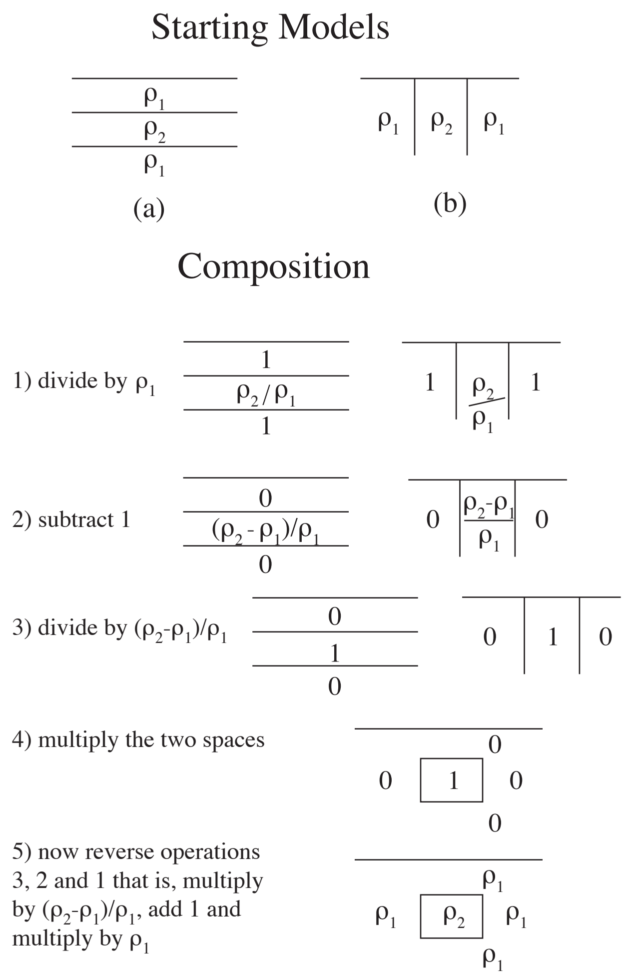


Fig. 14 - Composition rules applied to a concealed tunnel.

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