PARA DESENVOLVER A TERRA

MEMÓRIAS E NOTÍCIAS DE GEOCIÊNCIAS NO ESPAÇO LUSÓFONO

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THE USE OF GEOPHYSICAL ELECTRICAL METHODS IN THE CHARACTERIZATION OF AN ALLUVIAL AQUIFER IN A CRYSTALLINE ROCK ENVIRONMENT

O USO DE MÉTODOS GEOFÍSICOS ELÉCTRICOS NA CARACTERIZAÇÃO DE UM AQUÍFERO ALUVIAL EM AMBIENTE DE ROCHAS CRISTALINAS

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Abstract – In crystalline rock environments local alluvial deposits may be valuable as water reservoirs. Within the deposits the most favourable porosity - permeability relationships are generally associated with coarse-grained sediments. Unconsolidated sediments usually show a correlation between grain size and the electrical resistivity of the materials. Apparent resistivity mapping with an AB=20m array together with local Schlumberger electrical soundings put in evidence lateral variations in alluvium composition. However, it was also observed that variations in depth to water level may have a significant influence on apparent resistivity values. This influence must therefore be taken into account when making a regional scale analysis. Local scale apparent resistivity variations are viewed as particularly significant.

Keywords – Geophysics, electrical profiling, Schlumberger electrical soundings, alluvium, aquifer

Resumo – *Em ambientes de rochas cristalinas, depósitos de materiais aluvionares podem constituir reservatórios localmente relevantes no plano hidrogeológico. Nestes depósitos as relações porosidade - permeabilidade mais favoráveis encontram-se geralmente associadas com sedimentos grosseiros. Os sedimentos não consolidados apresentam geralmente uma correlação positiva entre o tamanho dos grãos e a resistividade eléctrica dos materiais. Foram feitos levantamentos com um dispositivo AB=20m, que conduziram à elaboração de uma carta de resistividades aparentes; realizaram-se também, localmente, algumas sondagens eléctricas Schlumberger. Estes levantamentos puseram em evidência a existência de variações laterais*

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na composição das aluviões. Contudo, observou-se também que variações na profundidade ao nível freático podem ter uma influência significativa nos valores de resistividade aparente obtidos. Esta influência deve, por conseguinte, ser tida em consideração ao fazer-se uma análise à escala regional. São particularmente significativas variações de resistividade aparente de âmbito local.

Palavras-chave – Geofísica, perfis de resistividade eléctrica, sondagens eléctricas Schlumberger, aluvião, aquífero

1 – Introduction

Water resources in crystalline rock environments are usually associated with fractures and fractured zones, and sometimes with a superficial thick weathered zone. In these areas local alluvial deposits may constitute valuable water reservoirs. The quality of such deposits as reservoirs is naturally related to their extent and thickness. It is also dependent on the nature of their constituting materials, particularly on grain size, and on their spatial distribution.

Alluvial deposits usually show an electrical resistivity contrast in relation to crystalline rocks. Moreover, within the deposits, there is generally a positive correlation between grain size and the electrical resistivity of the materials. These facts make it possible to use geophysical electrical methods to determine the lateral and vertical extent of alluvial deposits and to assess compositional variations within the deposits. This was a main objective of the surveys performed.

2 – Geological setting

The survey area is located in the centre-north of Portugal mainland, in the foot zone of the *Serra da Estrela*, near the village of Arcozelo (Gouveia) – see Fig.1. Regional lithology is mainly granitic. Late Pre-Cambrian to Cambrian phyllites and metagreywackes from the *Complexo Xisto-Grauváquico* outcrop in the sierra flank. The materials that make up the alluvial deposits under concern have their origin in these rock types. The deposits overlay a medium-grained, biotitic, porphyritic, monzonitic granite with feldspar phenocrysts and minor muscovite. The granites are late to post-Hercynian. They were subjected to late Hercynian brittle deformation and younger tectonic reactivation episodes. The main fault directions in the area are NE-SW and NNE-SSW.

Some patches of arkosic argillaceous deposits are locally present in the foot zone of the sierra. These deposits, that once formed a more continuous body, are associated with the Miocene uplift of the *Serra da Estrela* and the erosion of the granites. Taking into account the works of CARVALHO *et al.* (1983) and CUNHA (1992) their age is attributed to the Upper Miocene-Quaternary but it is admitted that older deposits from the Eocene-Lower Oligocene and Middle Miocene may be present. In the NW of the small basin of Arcozelo there are still some remains of an arkosic argillaceous deposit. These deposits are frequently very heterogeneous, particularly in grain size, showing a significant clay fraction.

The alluvial deposits of Arcozelo have a mean thickness around 6-8m. They show an upper fine-grained soil level. Sand levels and gravel levels are present in laterally varying proportions.

3 – Essential theory

The geophysical methods used include electrical profiling and electrical sounding techniques, both making use of a Schlumberger array. From a theoretical viewpoint, the measurement of the electrical resistivity with such a four electrode array is based on the expression for the potential created by a surface point current source. We shall review briefly the case of a continuous current flowing in a homogeneous isotropic medium, also applicable to low frequency alternating current. From Ohm's law we have that

$$\mathbf{J} = \sigma \mathbf{E} \quad 1)$$

where **J** is the current density (in A/m^2), **E** the electric field (in V/m) and s is the electrical conductivity of the medium (in S/m). For a point electrode delivering *I* amperes located at the surface of the homogeneous isotropic half-space (the return current electrode is considered to be placed at the infinite) current flow lines spread radially from the point current source. Considering a hemispherical surface of radius *r* centred on the point electrode, we have that

$$J = \frac{I}{s} = \frac{I}{2\pi r^2} \text{ and } E = -\frac{dV}{dr} \quad (2), (3)$$

where *I* is the total current passing through the hemispherical surface of area *s*, and *dV/dr* is the potential gradient across the hemispherical surface. From the previous relations we can write (taking $\rho = 1/\sigma$, the electrical resistivity of the medium)

$$dV = -\frac{I\rho dr}{2\pi r^2} \quad (4)$$

Integrating, and taking $V = 0$ at r = ¥, we get for the potential at a distance *r* from a surface point current source

$$V = \frac{I\rho}{2\pi}\frac{1}{r} \quad (5)$$

Considering now two current electrodes A$^+$ and B$^-$ at a finite distance from one another, the first sending a current of intensity *I* into the ground and the second the return current electrode, we will have for the potential at a point P at distances r_1 and r_2 from A$^+$ and B$^-$

$$V = \frac{I\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \tag{6}$$

For an in-line four electrode Schlumberger array A, M, N, B, with M, N the potential electrodes across which is measured a potential difference D*V*, we finally get the expression

$$\rho = K\frac{V}{I} \tag{7}$$

where $K = \pi\left(\overline{AM}.\overline{AN}\right)/\overline{MN}$ is the array constant. This is the expression for the electrical resistivity of a homogeneous isotropic terrain for measurements performed with a Schlumberger array. For inhomogeneous terrains the same expression is used, but instead of obtaining the resistivity r of the ground we now obtain a new parameter r_a, called the apparent resistivity. The apparent resistivity of an inhomogeneous ground may reflect the influence of several ground sectors with different resistivities but it is not an average value. It will depend, namely, on the electrode spacings and the depth of investigation of the array used. For a given terrain and a Schlumberger array, depth of investigation will increase with increasing current electrodes spacings. For a fixed array spacing, depth of investigation will generally be higher for a ground with high resistivity upper layers, when compared to a low resistivity upper layers situation.

4 – Profiling results

Apparent resistivity mapping over the alluvial deposits covered a surface of approximately 1000m per 500m average width. Profiling was performed with a fixed spacing AB=20m array; the MN spacing was 4m. With this array spacing depth of investigation is shallow enough for the terrain underneath the alluvium to have a low influence on the measurements. On the other hand, when using a fixed array spacing depth of investigation is kept overall constant (in reality there may be some small variations). As so, we may associate lateral changes in apparent resistivity with variations in alluvium composition.

The AB=20m apparent resistivity map is shown in Fig.1. In this map, the low apparent resistivity values observed to the north (< 70-100Wm) are associated with the arkosic argillaceous deposits. These deposits are also present, although not continuously, along a narrow strip on the western part of the map. To the east of the stream (excepting the extreme south), apparent resistivity values over 800Wm, and partially those over 400Wm, are associated with the granites that laterally delimit the deposits. High apparent resistivity values in the extreme NW are also related to granites. Apparent resistivity values of the alluvial deposits show a gradation from the SW to the NE: at the extreme south, alluvium apparent resistivities are in the order of those shown by the granites, reaching values over 800Wm; in the centre-north of the map values come under 140Wm.

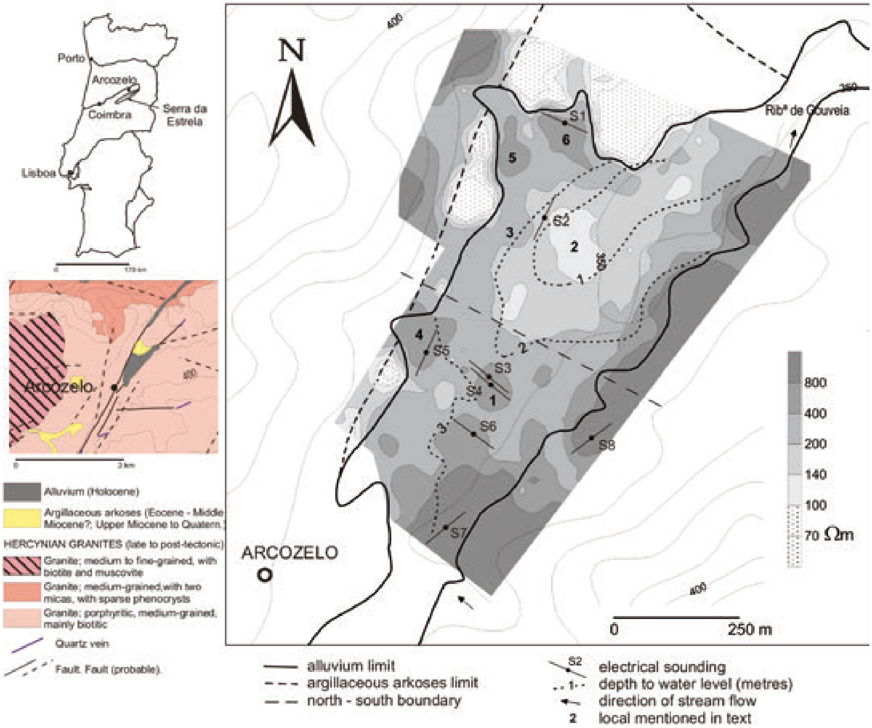

Fig. 1 – Schlumberger AB=20m apparent resistivity map of the study area.

There is a general relationship between sediment grain size and the resistivity of unconsolidated formations (table 1). A partial saturation, the presence of clay minerals in varying proportions and the higher/lower salinity of infilling water may cause considerable variations in the resistivity of sand and gravel deposits. Taking into account the composition of the alluvial deposits previously mentioned, sand and gravel levels could be expected to have resistivities in the range of 200 to 300Wm. This is confirmed by electrical soundings. Locally, those values may even reach 400Wm.

In this context, it could be admitted that in the areas with apparent resistivities over 200Wm sediment grain size would be for the most in the range of sand+gravel. Areas with apparent resistivities lower than 200Wm, and particularly for values lower than 140Wm,

Table 1 – Electrical resistivities of unconsolidated sediments, in Wm. (1) - after MEYER DE STADELHOFEN (1991); (2) - after ASTIER (1982); (3) - after ORELLANA (1982)

	(1)	(2)	(2)	(3)
	saturated formations	* with fresh water	dry	
Clay	5 - 10	2 - 20		1 - 50
Sand	50 - 400	50 - 500*	1000 - 10000	100 - 1000
Gravel	150 - 500	50 - 500*	1000 - 10000	100 - 10000

would correspond to finer-grained deposits. However, the situation turns out to be not so simple, as can be seen from an analysis of the relation between apparent resistivity values and the depth to water level in wells.

In the site of S3 (zone **1**; see Fig.1), an apparent resistivity of 525Wm was measured with AB=20m profiling, for a water level depth of 2.3m. In the same site, at a different moment, the value measured was 195Wm, for a water level depth of 1.1m. Similar measurements in the sites of electrical soundings S5 and S6 are represented in table 2. In this context, a correlation was sought between apparent resistivity values and water level depth (Fig.2). For 36 measurement points in the northern region of the alluvial deposits (region to the NE of the broken line in Fig.1, except for zones **5** and **6**) the correlation coefficient obtained was r = 0.86. In this region, the lower water depth values, less than 1m, were measured in the central zone **2** with apparent resistivities below 140Wm. The highest depth values, between 2 and 3m, were measured in the lateral zone **3** with apparent resistivities in the range 200-400Wm.

Table 2 - Relation between apparent resistivity and depth to water level.

	AB=20m profiling		Electrical soundings	
	App. Res. (Wm)	Depth to water level (m)	App. Res. for AB/2 = 10 (Wm)	Depth to water level (m)
Site of S3 (1)	525	2,3	195	1,1
Site of S5 (4)	650	?	300	?
Site of S6	500	2,5	210	1,4

These results point out that for depths of investigation in the range of those of an AB=20m array, variations in water level depth of 1 to 2 metres may have a significant influence on apparent resistivity values. As so, the differences in alluvium composition between zones **2** and **3** may be much more subdued than apparent resistivity values suggest.

Taking into account the whole area of the alluvial deposits the correlation coefficient is r = 0.29. This indicates that in the southern region, in addition to the influence of water level

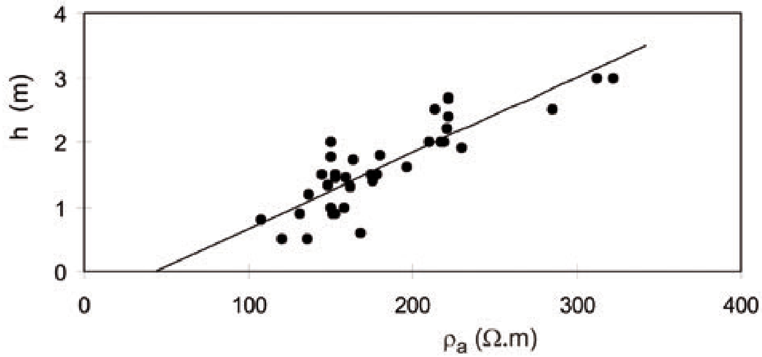

Fig. 2 – Apparent resistivity (r_a) versus depth to water level (h). r_a values measured with an array spacing AB=20m. Correlation coefficient r = 0.86.

variations on apparent resistivity values, there is a superimposing effect on the measured values, most probably related to a lateral variation in alluvium composition.

Besides these overall relationships, there are some significant local variations, as in the areas marked as **4**, **5** and **6**, which show apparent resistivity values higher than 400Wm. They are situated on the edge of the alluvial deposits, in the zone of slope break of three lateral thalwegs. They correspond to small alluvial fans. Nevertheless, the main point of sediment supply of the small basin is in the south, where the alluvial deposits show the highest apparent resistivity values (over 800Wm) and the larger thicknesses. Taking into account the position of the points of sediment supply, it is noticeable that the apparent resistivity variations of the alluvial deposits in the southern part of the map are mainly related to the main point of supply of the basin. The lower apparent resistivity values are associated with those areas further apart from both the main point of sediment supply and the secondary ones. It is therefore plausible that in these areas there is a joint effect of a shallower water level and a higher proportion of fine-grained sediments.

5 – Electrical sounding results

Electrical soundings at specific sites allowed to cross depth targeted information with lateral variations in the AB=20m apparent resistivity map (see Fig.1 for location).

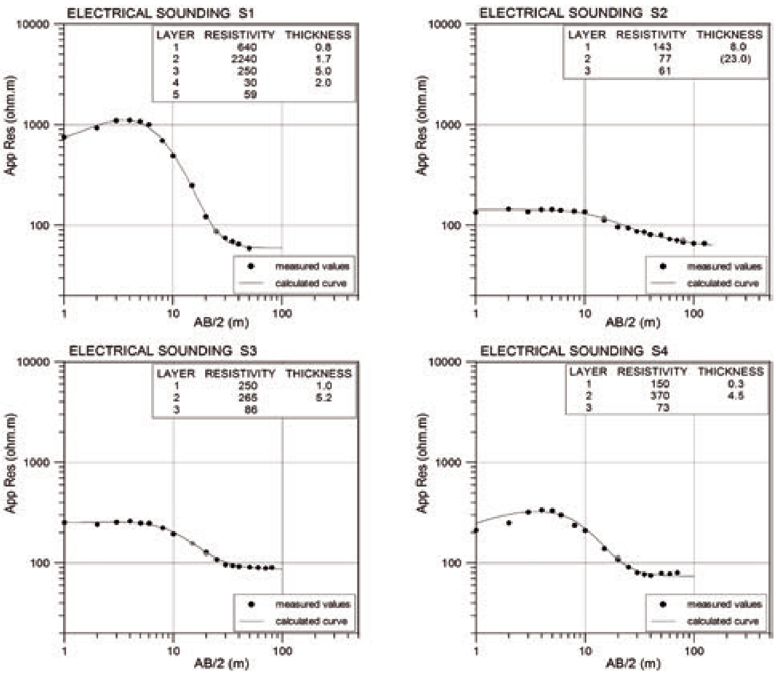

Fig. 3 – Electrical soundings S1 to S4 (see Fig.1 for location). Electrical resistivity in ohm.m; thickness in metres. Values in brackets: lateral effects.

It is a conspicuous feature of the electrical soundings in Figs.3 and 4 the presence of a low resistivity terrain under the upper higher resistivity alluvial layers. This terrain is related to a NNE major fault and it corresponds to a wide fault zone low resistivity material (ALTE DA VEIGA, 1999).

Arkosic argillaceous deposits are also present in the small basin of Arcozelo, at higher levels than the alluvial deposits. They correspond to the remains of a once more important deposit that was eroded by the deepening of the stream system. The argillaceous arkoses characteristically show very low electrical resistivities, under 40Wm. They are absent from the curves of the electrical soundings performed over the alluvial deposits. The exception could be sounding S1. At most, they could be present under the alluvium as a thin layer that would be suppressed in electrical soundings.

A comparative analysis of electrical soundings S3 (zone **1**, in Fig.1) and S2 (near zone **2**) shows clearly that a variation in alluvium composition between the two places must exist. For a similar water level depth at the two sites, an alluvium resistivity of 260Wm was obtained in sounding S3 against 140Wm in sounding S2. This indicates the presence of a higher proportion of coarse-grained sediments in the area of S3.

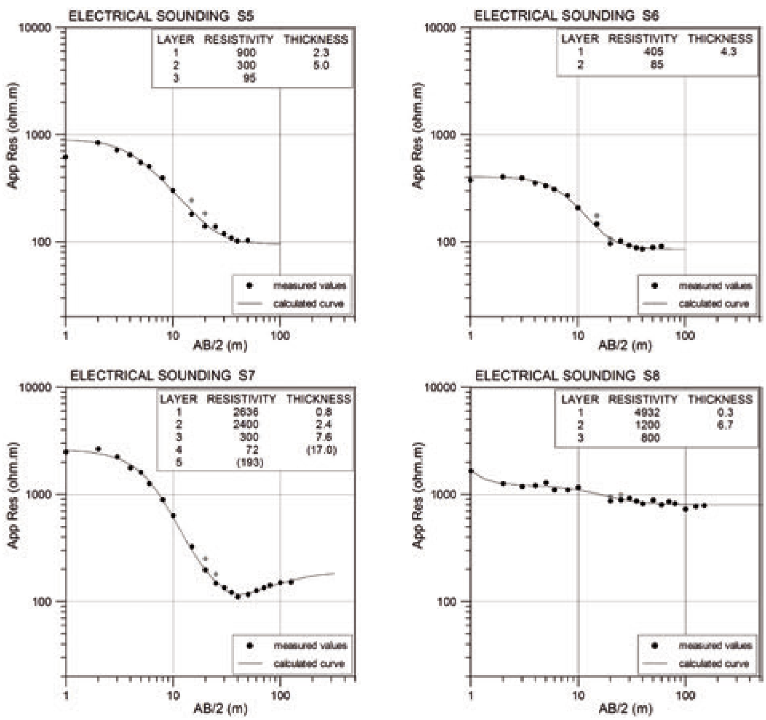

Fig. 4 – Electrical soundings S5 to S8 (see Fig.1 for location). Electrical resistivity in ohm.m; thickness in metres. Values in brackets: lateral effects.

Comparing soundings S3 and S4, the alluvium thickness in the first case has a value of 6.2m for a resistivity of 265Wm (layer 2) against 4.8m and 370Wm (layer 2) in the second case. The two soundings are close to one another and water level depth is similar for both places. This implies the existence of some variation in alluvium characteristics between the two places. A variation in alluvium thickness would also be possible, but from a global comparative analysis of the electrical soundings performed at Arcozelo the existence of an effect related to sounding curve shape can be inferred. In similar conditions, soundings presenting an initial flat curve and a relatively weak resistivity contrast between that first layer and the second layer will show higher alluvium thicknesses. In soundings of type K, as sounding S4, and/or showing a higher resistivity contrast between the alluvium and underlying terrains, layer suppression will be facilitated.

Schlumberger soundings performed over the alluvial fans and the zone marked as **1** are in agreement with a coarse-grained nature of the sediments in these areas. Resistivities for the alluvium show values between 250 and 405Wm for soundings S5 (over zone **4**), soundings S3 and S4 (zone **1**), S6 (to the SSW of zone **1**); sounding S7 (at the extreme south of the map) and S1 (over zone **6**). Characteristically, upper non-saturated layers reach high resistivity values, in the range 900-2600Wm for soundings S5, S7 and S1. In what concerns thicknesses over alluvial fans, sounding S5 (zone **4**) puts in evidence 7.3m thick deposits, the S1 (zone **6**) 7.5m, and sounding S7, at the extreme south, the major thickness – 10.8m. The last value and the layer resistivities in sounding S7 are in agreement with the description of the log of a well located close to the sounding. It mentions the existence, over a depth of 8m, essentially of pebble-cobble layers.

It has been pointed out that at the extreme south of the map in Fig.1 apparent resistivities of the alluvial deposits are in the same range of those of granites. Distinction between the two situations may be readily done from the electrical sounding curves. Sounding S7 (over alluvium) shows a clearly different pattern from sounding S8 (over granite).

6 – Conclusion

The spatial variation in the composition of alluvial sediments may be quite pronounced. From the general relationship between the resistivity of unconsolidated formations and sediment grain-size it is possible to make use of geophysical electrical methods in their differentiation, which was here clearly achieved. This possibility is of major interest as, in general, the most favourable porosity - permeability relationships are associated with coarse-grained sediments.

Besides the electrical resistivity variation with the type and thickness of sediments, it has been shown that, for relatively shallow depths of investigation, water level depth has a definite influence on apparent resistivity values. Thus, it is considered that, in general, apparent resistivity variations on a regional scale should be looked at with some reserve. Local variations, such as those mentioned in zones **1**, **4**, **5** and **6** are viewed as being particularly meaningful.

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