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Chapter 6

ERT and the Location of Mining Cavities in Anisotropic Media: A Field Example

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Abstract

Often cave location requires the use of surface indirect techniques, such as geophysical methods. In particular, electrical methods have been applied to cavity exploration with evident success. However, as any other indirect methods, the use of these techniques has advantages and disadvantages. Cavities may be too small, too deep or masked by local geology to be detected. Nevertheless, indirect methods provide non-invasive, low cost and fast techniques to carry out the reconnaissance of an area where the presence of cavities is suspected. Complex geological conditions and formations anisotropy can induce strong orientational variation on ground resistivity measurements and, therefore, mask the presence of caves. Herein a field study in an old mining area demonstrates that 2D resistivity data—electrical resistivity tomography (ERT)—can be strongly affected by local anisotropy that masks the presence of cavities in ERT data modelling. In these cases, specific field strategies must be considered to overcome misleading interpretations and modelling, so that, meaningful results are obtained, uncertainty and interpretation ambiguity are reduced and the correct diagnosis of caves is accomplished.

Keywords: exploration, cavity, orientation, ERT, anisotropy

1. Introduction

The importance of cavities in engineering, mining, environment, archaeology, tourism, etc. has long been acknowledged. Caves have natural origin (lava, karst or other dissolution processes) or can originate from anthropic activities, such as mining, engineering excavations and archaeological features.

Knowledge of cave location and extension is very important during the construction and maintenance of infrastructures (tunnels, highways, railways, sewage systems) and when urban areas extend to old mining areas or karst regions. In fact, risks of collapse and pollutants transportation can lead to unwanted and hazardous events. Caves are also used as reservoirs, deposits of gas, hazardous and toxic residues and, therefore, cavity monitoring and four-dimensional (4D) studies must be considered for safety reasons.

Cavity location is often done by surface mapping, documents, local and oral descriptions. Therefore, before engaging in expensive and comprehensive exploration programmes, it is important to review all the relevant available information. However, often local records are difficult to obtain, particularly in old mining areas. It is also possible that no information is available in regions with no evidence of caves at the surface or in cases of fast cavity development, such as sinkholes.

Often invasive exploration methods (excavation, drilling) are used. These invasive methods must be carefully planned to reach the targets at a suitable cost and, furthermore, operations must not interfere and damage the caves [1].

Other approach uses indirect investigation techniques from the surface that is geophysical exploration methods. However, the efficiency of these methods depends, among other factors, on the contrast between the physical properties of the cavities and those of the surrounding media [2].

Fortunately, in most cases there is a contrast between the velocity of seismic wave propagation, density, electrical and magnetic properties of the cavities and those of the rock formations where they are installed [3] and, thus, geophysical exploration methods can be used and adapted to cavity detection and location [4]. However, the relation between the dimensions of the cavities and their depth can also be a major limitation factor for the use of geophysics. In fact, cavities can be too small or too deep to be detected in spite of a large contrast in physical properties [5].

Since these limitations are overcome, the main objective of the use of geophysical methods in cavity location is to provide information and restrict the area to investigate by direct methods, to guide later exploration operations and to diminish costs while preserving the targets [6].

In this contribution, the application of geophysical methods in cavity exploration is focused on the use of 2D resistivity methods—electrical resistivity tomography (ERT).

There many examples of the use of 2D and 3D ERT in cavity location [7, 8]. As in any other geophysical method, the success of cavity detection by resistivity methods depends on factors such as depth, size and contrast between the resistivity of the cavity and that of the surrounding media [5]. Cavities can be more conductive or more resistive then the rocks that surround them. Cavities filled with water are more conductive then the surrounding media. However, when empty they are more resistive as air is not an electricity conductor. Thus, in the first case, cavity response to resistivity methods is a conductive anomaly whilst, in the second case, the response will be a resistive anomaly.

The nature of the surrounding media is another factor to consider. Usually, resistivity fieldwork consists on recording data in one unique direction. Therefore, two-dimensional effects arising from local geology such as contacts, schistosity, etc., can induce orientational variation on surface resistivity data and complicate cavity detection.

In the past, resistivity fieldwork was a slow operation. Nowadays, the development of automated equipment allows the fast acquisition of large field data sets. This enables the production of high-resolution images of the ground and answers the engineers' and planners' needs for fast, non-intrusive and high-resolution methods to detect underground targets such as cavities.

This work will give a brief introduction to the resistivity methods and to the field techniques necessary to carry out an ERT. Then an approach to the resistivity behaviour in anisotropic media is presented. Finally, a case study concerning the location of mining cavities in anisotropic regions is discussed. The ambiguity and uncertainty in the ERT interpretation will be addressed and field strategies to reduce or overcome those limitations are also presented.

2. Basic theory of resistivity methods

Resistivity measurements are traditional geophysical methods. There are extensive textbooks presenting the theory of electrical methods [9] and their use in engineering and environmental investigations [10].

In broad terms, resistivity methods consist on passing a DC current into the ground using two current electrodes and measuring the generated electrical potential between two potential electrodes, **Figure 1**.

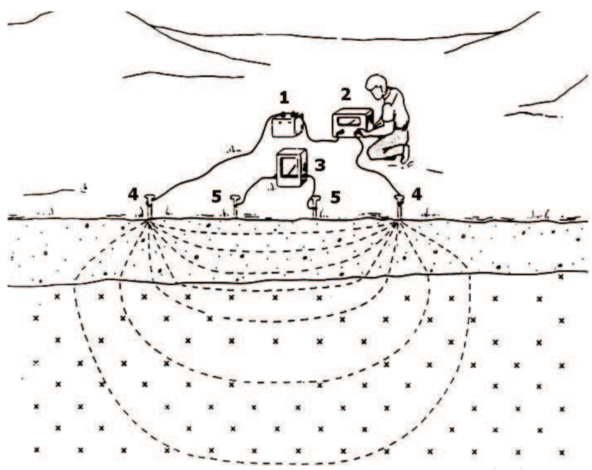

Figure 1. Resistivity fieldwork; 1, battery; 2, ammeter; 3, voltmeter; 4, current electrodes; 5, potential electrodes; dashed lines, current lines in the ground.

In the past, resistivity field operations were slow and tedious but the development of computer controlled multi-electrode resistivity metres and cables, **Figure 2**, enables fast field operations and the recording of large data sets.

Usually, field measurements use four in-line electrode arrays. The commonest in-line electrode arrays are the Wenner (left of **Figure 3**) and Schlumberger (right of **Figure 3**).

Figure 2. Resistivity equipment: left, automated resistivity metre and cables; right, stainless steel electrodes.

Figure 3. Resistivity arrays: left, Wenner; right, Schlumberger.

In the Wenner array, the electrodes are equally spaced, 'a', whilst in the Schlumberger array the distance AB, between the current electrodes, is larger than the distance between the potential electrodes MN. Once the potential difference, V, and the current, I, are measured the resistivity of the ground, ρ, is

$$\rho = 2\pi a \frac{\Delta V}{I} \quad \text{for the Wenner array} \tag{1}$$

and

$$\rho = \frac{\Delta V}{I} \pi \frac{(b+a)}{a} \quad \text{for the Schlumberger array} \tag{2}$$

The construction of an ERT requires the use of Wenner and Schlumberger arrays of different sizes along an acquisition line of electrodes, **Figure 4**.

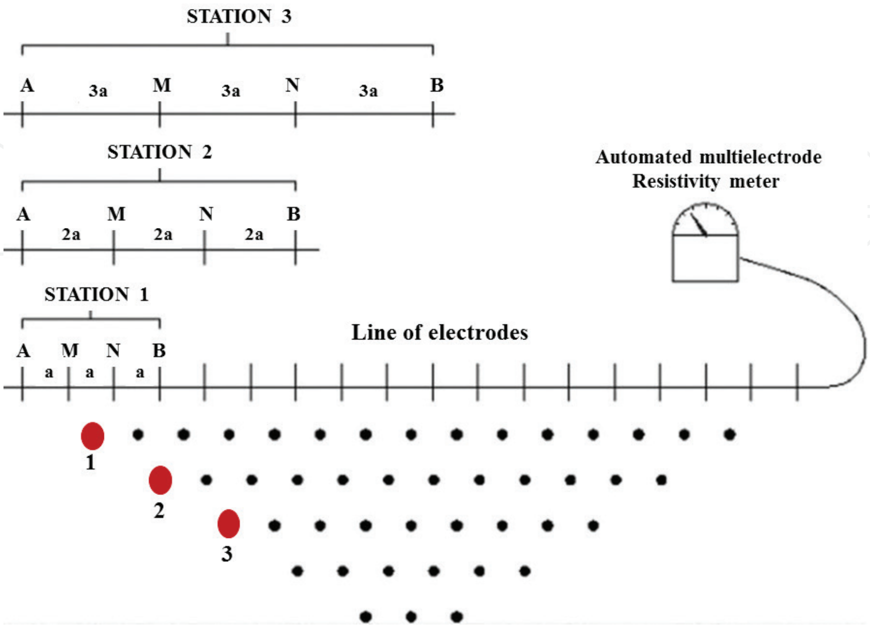

Figure 4. Construction of an electrical resistivity tomography—ERT.

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As depicted in **Figure 4**, the first line is obtained by moving the electrode array, using an electrode spacing 'a', along the line of electrodes. The measurements are plotted in accordance with the centre of the array and the spacing 'a' used, first line in **Figure 4**. The first measurement corresponds to the red dot 1, station 1.

When line 1 is finished, field measurements resume with line 2. Now, the electrode array spacing is '2a' and data are plotted against the position of the centre of the array and the new spacing '2a'. The first measurement corresponds to the red dot 2, station 2.

The procedure continues until reaching the number of lines required to obtain an image—ERT—of the ground.

To optimize field measurements, it is usual to combine Wenner and Schlumberger arrays. The complete procedure is controlled by an automated multi-electrode resistivity metre previously programmed to carry out the complete sequence of field measurements and to store all field information.

Once all data are stored, they can be modelled using appropriate software [11, 12] and detailed information about the ground is obtained.

Often cavities are installed in heterogeneous and complex media. In these cases, resistivity measurements can vary with the orientation of the line of electrodes, as shown in **Figure 4**. In such cases, the orientational variation of resistivity data can hinder the location of cavities and, possibly, mask their presence.

In the presence of anisotropic media, steeply dipping schists are a good approximation, it is usual to consider two resistivities: one ρ_l the longitudinal resistivity, in the direction of the strike, and another ρ_t, transverse resistivity, perpendicular to the strike [13], **Figure 5**.

As the longitudinal and transverse resistivity values are different, it is possible to define a mean resistivity ρ_m:

$$\rho_m = \sqrt{\rho_t \, \rho_l} \tag{3}$$

and an anisotropy coefficient, λ, the square root of the ratio between ρ_t and ρ_l:

$$\lambda = \sqrt{\rho_t / \rho_l} \tag{4}$$

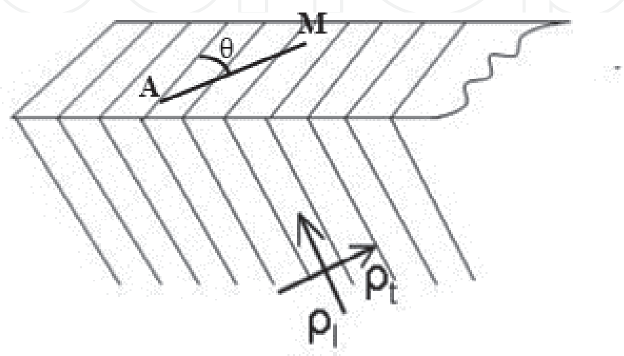

Figure 5. Anisotropic medium: ρ_l, longitudinal resistivity; ρ_t, transverse resistivity; A, current electrode; M, potential electrode; θ, array orientation.

In the field, resistivity values can vary largely with the orientation θ of the line of electrodes, **Figure 5**, and the coefficient of anisotropy can reach values larger than 2 [9, 13].

The influence of anisotropy on resistivity measurements has been investigated [14, 15] and, herein, a case study on the location of old mining cavities in anisotropic media will be presented [16].

3. Cavity detection in anisotropic regions: a field example

Slates mining in Valongo (41°11′N, 8°30′W, 30 km North of Oporto, North Portugal) started in the nineteenth century. Since then many underground works were abandoned and no records are left about their whereabouts and extension. Slates of economic value occur in steeply dipping Ordovician schists where strong orientation effects of physical properties and anisotropy occur.

Increasing urban development pressure requires information about the position and extension of mining chambers but, documents about older works are scarce and field interventions demand the use of fast and non-invasive methods that is geophysics.

Electrical tomography techniques (ERTs) using the Wenner-Schlumberger array were used to investigate the dimensions of an old mining chamber. Today, the only evidence of the chamber at the surface is the shaft and the possible lateral limits of the underground works, depicted by the dashed line in **Figure 6**.

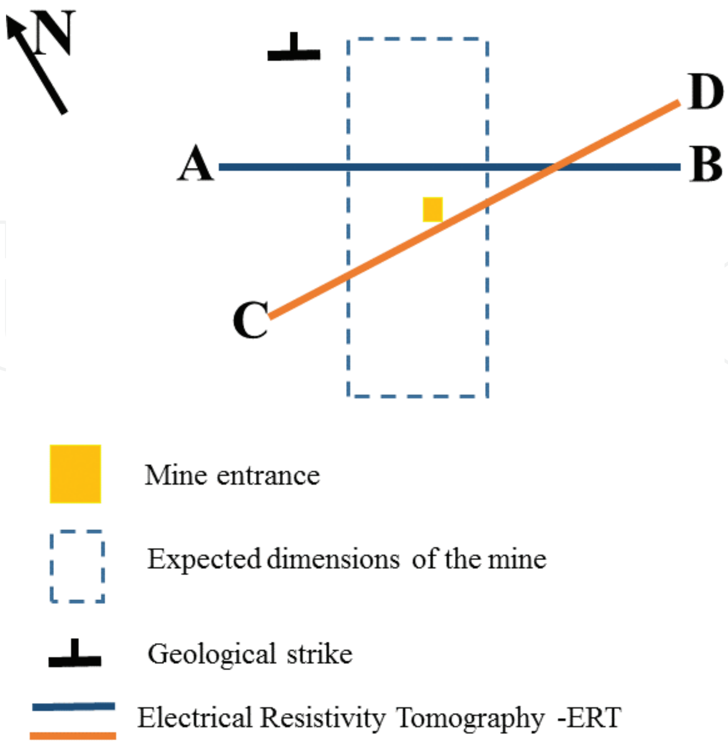

Figure 6. Mine chamber and ERT location in Valongo.

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Figure 6 also shows the mine entrance (central gray rectangle), the position of two ERTs, AB and CD, and the geological strike. Inspection of the shaft revealed that the mine is flooded and the groundwater level is very close to the surface. Thus, a large contrast between the cavity (conductive) and the surrounding rock (resistive) is expected. So a conductive anomaly is expected.

Because of access difficulties, a first ERT, AB in **Figure 6**, was carried out parallel to the geological strike and, in these conditions, values corresponding to ρ_1 should have been measured. Data were inverted using the software RES2Dinv [12], and the model is shown in the left of **Figure 7**.

The model shows a resistive layer overlaying a conductive formation. The boundary, shown by the dashed line in the left of **Figure 7**, is at the same depth of the groundwater in the chamber entrance.

As the ERT orientation is parallel to the strike, the modelled resistivity should correspond to the longitudinal resistivity, ρ_1. Therefore, longitudinal resistivity values must be higher above the groundwater level. However, they must decrease sharply below that level as a response to the water in the chamber and in the schists' foliation. Hence, this boundary is interpreted as the groundwater level.

Below this boundary, no more relevant information is obtained from the ERT model as only a conductive medium is shown.

Thus, tomography AB does not give evidence of the chamber and, if only this ERT was carried out, the location of the chamber would have been completely missed.

Therefore, it was decided to conduct a second ERT, CD in **Figure 6**. Because of access difficulties, CD orientation was at approximate 45° to the geological strike. The same field technique was used and model results are depicted in the right of **Figure 7**. In this case, a conductive body, bounded by the dashed lines, is clearly shown and stands out from the resistive surrounding rocks.

At shallow depths, a resistive layer is depicted with the same thickness in both ERTs. Bearing in mind the previous discussion, this layer corresponds to the resistive ground above the groundwater level.

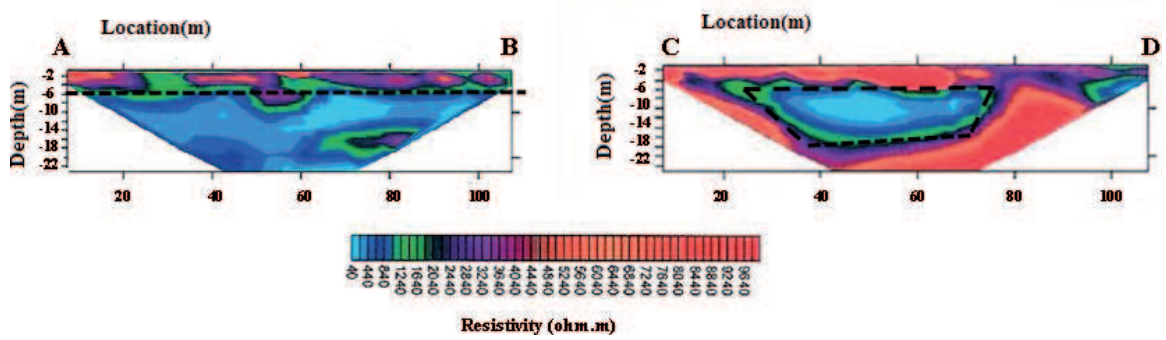

Figure 7. ERT models in Valongo: left, AB (dashed line, groundwater level); right, CD (dashed line, interpreted cavity dimensions).

As the chamber is filled with water, the conductive anomaly should correspond to the mining chamber and, in fact, the proposed lateral boundaries match the expected limits of the dashed line in **Figure 6**. The higher resistivity values recorded away from the conductive anomaly refer to the schists' resistivity as measured with this ERT orientation.

Because of the orientation used, modelled resistivity values in CD do not correspond to the transverse resistivity of the schists. Therefore, it is not possible to calculate the anisotropy coefficient, but an indication of field anisotropy values can still be computed by calculating the square root of the ratio between the modelled resistivities for CD and AB.

Thus, a further section was constructed depicting the square root of the ratio between the resistivities modelled in the two ERTs.

Figure 8 shows ratio values varying from 1 to more than 3.4. Thus, although this is not the anisotropy coefficient, field conditions are highly anisotropic.

The high resistive shallow layer, above the groundwater level, should correspond to ratio values close to 1. In this case, resistivity values modelled for AB and CD refer to a 'dry' or non-saturated area and, thus, should be similar. Hence, the dashed red line in **Figure 8** must correspond to the groundwater level as shown in **Figure 7** and, above this boundary, ratio values vary from 1 to 1.4. These values are considered to correspond to a low anisotropic medium [13, 17].

The central area of the section displays resistivity ratio values near 1 (or less than 1). This area corresponds to the position of the chamber depicted in the right of **Figure 7**. As the chamber is filled with water, resistivity values modelled for AB and CD ERTs should be similar as they correspond to data in the conductive chamber region.

It must be noted that ratio values less than 1 are depicted in **Figure 8**. This behaviour has been registered where structural anisotropy prevails [13, 17], such as in the vicinity of interfaces separating media with high resistivity contrast. In these circumstances, there is a rotation of the anisotropy axis and the so-called oblate anisotropy is observed [13]. This should be the

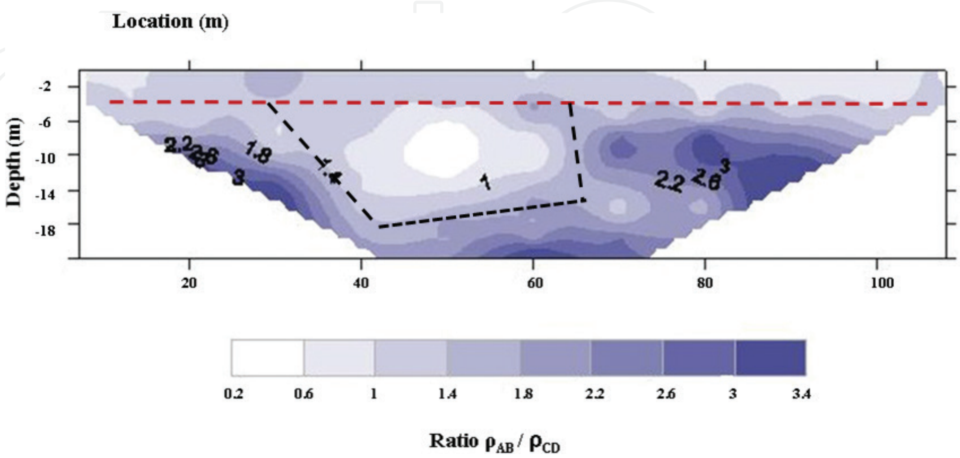

Figure 8. Ratio between modelled resistivities in Valongo; dashed line, proposed cavity limits.

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case in the field example as the contact between the conductive chamber and the highly resistive surrounding rock corresponds to an interface separating two media with a very high resistivity contrast.

Away from the chamber position, ratio values increase as it should be expected. Therefore, one direction—AB—corresponds to the resistivity in the foliation planes (lower values), but the other direction—CD—is closer to the transverse resistivity (higher values).

There are many examples of the use of conventional ERT techniques in the location of mining cavities with evident success. However, the influence of formation anisotropy is seldom addressed and can mask ERT response. In this case, different field ERT orientations must be used to avoid misleading interpretations.

Often field space is restricted and only one ERT can be carried out. In this case, ERT orientation must be rather different from the strike of the geological formations and, in optimal conditions, ERT orientation should be perpendicular to the strike.

It is also possible to use electrode arrays that take into account orientation effects and anisotropy. Therefore, sets of linear arrays covering a wide range of directions can be used [14]. Alternatively, arrays of different geometry such as the square array have also been proposed [13].

However, the use of alternative arrays demands space and easy field access conditions and this requirement can be difficult to meet in urban areas.

4. Conclusions

Geophysical methods are a powerful tool for cavity location. They provide fast, economic, automated, non-invasive techniques that offer relevant information to restrict areas of interest and, thus, to guide more expensive direct exploration methods. As non-invasive methods, they do not require excavation or drilling and thus can be adapted to operate in urban areas.

These methods are indirect techniques as they measure the difference in physical properties between the cavities and surrounding media and not the properties of the cavities themselves. Fortunately, most of the times, there is a contrast between the physical properties of the cavities and those of the surrounding rocks. However, the size and depth of the cavities can be a limiting factor for the use of geophysical methods.

The complexity of the geology formations where the cavities are installed can be another limitation factor as demonstrated in this case study. Therefore, orientational effects and formation anisotropy can mask cavity response inducing ambiguity and uncertainty in the interpretation. In this case, field survey design must be carefully planned to overcome or reduce orientational effects in the final interpretation, to avoid misleading interpretations and the use of alternative non-linear arrays must be considered.

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