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## ► To cite this version:

Thomas Hauquin, Quentin Mourey. The detection of old masonry tunnels as low electrical resistivity anomalies-application to one covered stream tunnel of the Cevennes Mountain region (France). *Journal of Applied Geophysics*, 2019, 168, pp.12-23. 10.1016/j.jappgeo.2019.05.010 . hal-02436521

**HAL Id: hal-02436521**

**<https://imt-mines-ales.hal.science/hal-02436521>**

Submitted on 25 Oct 2021

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# **The detection of old masonry tunnels as low electrical resistivity anomalies – Application to one covered stream tunnel of the Cevennes Mountain region (France)**

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**Keywords:** 2D-ERT, Old masonry tunnels, Thin conductive layer, Forward modelling

## **Abstract**

More than 70 km of old masonry tunnels covering natural streams were recently inventoried in the Cevennes mountain region (France, *département du Gard*). Due to their advanced state of degradation and their shallow depth, the covered stream tunnels have been responsible for several surface collapses since 2012. The mapping of the trajectory of these tunnels therefore is of primordial importance for the risk assessment of the affected municipalities. But only few of them were mapped so far due to their difficult accessibility and their precarious stability. Consequently there is a need to identify non-destructive methods for detecting them quickly from the surface of the most preoccupying areas. Two ERT profiles using 48 electrodes and the Wenner-Schlumberger array, under dry and wet conditions, were realized at the surface of one tunnel of which the position was precisely known in order to determine the ability of the technique to detect it. Analysis of the measured apparent resistivity showed an unexpected local decrease of resistivity near the tunnel boundary. The inverse models performed without any filtering of the measured apparent resistivity did not allow detecting any anomaly that could be interpreted as the presence of the tunnel. Conversely, the inversion of a smoothed version of the apparent resistivity allows detecting a low resistivity anomaly at the tunnel position. This result was quite surprising because we rather expected a high resistivity anomaly due to the infinite resistivity of the tunnel atmosphere compared

to the surroundings. According to a study recently published by Putiška et al. (2012) on this topic and to a set of forward resistivity models we conducted, this unexpected low resistivity anomaly was explained to be due to the presence of a thin conductive layer around the tunnel. The fact that this anomaly was unobserved after inversion of the unfiltered apparent resistivity was explained by the presence of a high resistivity material (probably composed of coal) beside the thin conductive layer that altered the least-squares inversion process.

## **1. Introduction**

### **1.1. Context**

The Cevennes mountain region was the locus of an intense coal mining during the 19<sup>th</sup> and 20<sup>th</sup> centuries. More than 70 km of old masonry tunnels – the covered stream tunnels – were built above natural streams in order to backfill the valleys with coal mine tailings and to build platforms for the mining related plants. The coal mines closed but the covered stream tunnels remain foundation for many houses and infrastructures.

Due to the progressive deterioration of the masonry, at least 3 covered stream tunnels collapsed since 2012 and 2 tunnels collapsed before that at an undetermined date (two examples in Fig. 1). We visited 30 of the larger covered stream tunnels and those where no collapse has yet occurred are often in an advanced state of damage indicating that future collapses will probably happen.

According to the last estimate (Vayssade et al. 2015) more than 500 buildings would be located at less than 50 m of the tunnels axes (at the surface) which are considered to be a zone of high risk. However, these zones were determined with a great uncertainty. Indeed, the access to certain tunnels is unsafe and requires specific equipment, so their trajectories were determined in an approximate manner, in function of the tunnels entrances and exits only. Moreover, small secondary

tunnels whose entrances were occasionally found, but that cannot be inspected due to their size and state of degradation, were ignored.

## 1.2. Problematic and objectives

An important issue is to identify non-destructive methods for locating precisely the tunnels positions in some specific zones of interest from the surface, and in particular the smallest tunnels of which the trajectory is the most uncertain.

Geophysical methods in general are known to be economic, rapid and effective for detecting shallow cavities or openings in various geological contexts (Orfanos & Apostolopoulos, 2012). Among the various geophysical techniques commonly used for detecting shallow cavities (microgravimetric, magnetic, seismic or electrical methods), the 2D Electrical Resistivity Tomography (2D-ERT) was selected in this study. 3D investigations were not necessary since the researched tunnels are long and most of the time linear with a small slope so we can assume that this is a plane problem.

The ERT technique has several advantages that made it attractive in the context of the present study: i) a sufficient resolution (depending on the chosen electrode array) in both the horizontal and vertical direction so that cavities can be positioned vertically and horizontally, ii) it is a quite rapid technique which does not require to spend a long time at the surface of the investigated areas which are prone to collapse, iii) the method is sensitive to a great resistivity contrasts such as those expected to occur between the tunnel atmosphere and the surrounding soil.

2D-ERT has already been demonstrated to be a reliable technique for the detection of metric cavities in anthropic areas (Nero et al., 2016; Ioannis et al., 2002; Boubaki, 2013; Bianchi Fasani et al., 2013), for the detection of mining cavities (Martinez-Pagàn et al., 2013; Bharti et al., 2016) and karsts (Gómez-Ortis & Martín-Crespo, 2012; Metwaly & AlFouzan, 2013), and for the detection of shallow concrete tunnels (Riddle et al., 2010). The ERT technique was also successfully used to detect partially filled old shafts (Amini & Ramazi, 2016). In all cases, cavities appear as a highly resistive

anomaly whose inversed resistivity depends on several factors such as the cavity diameter and the surrounding soil resistivity. The analysis of the published results shows that the depth of the investigated cavities is accurately identified by 2D-ERT in general and that it is an appropriate method of approaching the cavity extension where it is unknown.

Despite the significant number of publications related to the detection of shallow cavities with 2D-ERT, in our best knowledge, no study was published about the detection of old masonry tunnels such as the covered stream tunnels. So the present study tackled the following objectives:

- assessing the capability of 2D-ERT to detect old masonry tunnels,
- determining what type of resistivity anomaly is to be expected at the tunnel position,
- determining the conditions of a good detection.

### 1.3. Study plan

To answer these objectives, the study was organized as follows. First, we selected an adequate study site consisting of a tunnel of which we precisely know the trajectory in order to be able to assess the precision of its detection with 2D-ERT. We also identified a second tunnel in the same area that we were susceptible to detect but of which we didn't know the trajectory (Section 2). Then, we realized two 2D-ERT measurements along one profile perpendicular to the main tunnel axis under different weather conditions. The measured apparent resistivity was inverted with the RES2DINV software (Section 3). After that, we realized forward models with the RES2DMOD software with resistivity values based on small scale *in situ* measurements for the purpose of giving explanation to one unexpected result obtained after inversion of the measured apparent resistivity (Section 4). Finally, the combined interpretation of inverse and forward resistivity models led us to draw practical conclusions about the detectability conditions of old masonry tunnels with 2D-ERT (Section 5).

## 2. Method

### 2.1. Brief introduction of the 2D Electrical Resistivity Tomography (2D-ERT)

The 2D-ERT consists of measuring the apparent resistivity of the sub-surface by injecting a direct electrical current in the ground between two electrodes A and B (current electrodes) and measuring the induced voltage between two other electrodes M and N (potential electrodes). From the injected current  $I$  and the measured voltage  $V$ , the average resistivity ( $\Omega.m$ ) of the ground crossed by the current, i.e. the apparent resistivity, can be calculated as:

$$\rho_{app} = \frac{KV}{I} \quad (1)$$

where  $K$  is the geometric factor calculated as:

$$K = \frac{2\pi}{\left[\frac{1}{MA} + \frac{1}{MB} + \frac{1}{NA} + \frac{1}{NB}\right]} \quad (2)$$

The positions and spacing between the electrodes are successively varied in order to measure the apparent resistivity at different positions along a profile and at different depth levels.

From the measured apparent resistivity, an inverse model is conducted in order to estimate the true resistivity values of the sub-surface responsible for the measured apparent resistivity. Variations of the true resistivity are interpreted as a change of material or as a change of fluid condition within a given material.

The relative position of the current electrodes compared to the position of the potential electrodes defines the electrodes array. The most common arrays used for sub-surface investigations are the Wenner array (W), the Dipole-Dipole array (DD), the Pole-Dipole array (PD), the Pole-Pole array (PP), and the Wenner-Schlumberger array (WS). They differ mostly by their sensitivity to horizontal or vertical structures, their noise level and their depth of investigation (see Loke, 2016 for details). The apparent and inverse model resistivity both depend on the chosen electrode array.

## 2.2. Study site presentation

Our study site was located in Robiac-Rochessadoule (France, *département du Gard*, Fig. 2). There are 5 covered stream tunnels spread across the town, 2 of which having known large collapses or sinkholes in recent years. In order to assess the actual state of the tunnels in an obvious risky context, the municipality ordered a precise investigation of the tunnels including their precise topographic survey. So we know precisely the position, trajectory and depth of the tunnels.

Among the 5 covered stream tunnels, we selected the one with the most favorable features regarding the study objectives: the *Rochessadoule* tunnel (Fig 3). The tunnel is about 370 m long and consists of a semi-circular vault of 2.5 m radius relying on vertical sidewalls of about 1 m width and 1.5-2 m height. It is located under an easily accessible planar ground, with a quite homogeneous soil at the surface. The accessible ground length perpendicular to the tunnel axis is about 50 m, which allows having a sufficient distance between the electrodes for the depth of investigation (from 7 to 10 m depending on the chosen electrodes array) to be compatible with the tunnel depth (from 3 to 6 m depending on the distance from the tunnel entrance). Furthermore, the entrance of a small secondary tunnel of 1.2 m height was found next to the main tunnel entrance. We did not know its trajectory because it is partially collapsed and inaccessible a few meters after the entrance. But its entrance is almost parallel to that of the main tunnel, so we expected that would be able to detect it somewhere along the resistivity profiles.

We did not know the precise composition of the investigated soil. However, at least five material types were supposed to be present in the investigated zone:

- a thin homogenous layer of silt at the ground surface with an heterogeneous water saturation,
- a heterogeneous backfill material composed of coal mine tailings around the tunnel,
- an old masonry of 0.5 to 1 m width forming the tunnel structure, mostly composed of Triassic sandstone and mortar or concrete joints,

- the host rock of the tunnel composed of Triassic sandstone, and
- the atmosphere of the tunnel.

The atmosphere of the tunnel is supposed to have a very high, say infinite, resistivity compared to the other material types. The resistivity of the other material types was estimated *in situ* thanks to small scale electrodes arrays. The backfill material surrounding the tunnel was not directly accessible so its resistivity was estimated in a pile of unused material stored next to the studied sector (Fig. 4a). We supposed that the same material was used during the tunnel construction. The resistivity of the masonry was determined thanks to a 1D horizontal sounding realized by inserting small screws at the surface of the tunnel sidewall. Similarly, a horizontal sounding was realized on the vertical surface of the host rock flushing near the tunnel entrance. Table 1 summarizes the resistivity values obtained by averaging the result of various depths of investigation inside the *in situ* materials (from 25 cm to 1 m in the rock, the masonry and the backfill; from 10 cm to 50 cm in the silt layer).

**Table 1:** estimated *in situ* resistivity of the materials we were supposed to detect with the ERT.

| Material  | Tunnel<br>Atmosphere | Silt          | Backfill      | Host rock     | Masonry       |
|---|----------------------|---------------|---------------|---------------|---------------|
| Estimation of<br><i>In situ</i> resistivity<br>( $\Omega.m$ ) | $\infty$             | $\approx 100$ | $\approx 250$ | $\approx 700$ | $\approx 500$ |

### 2.3. ERT profiles characteristics

The ERT profile (Fig. 4b) was placed so that the main tunnel axis was in the center of the profile (Fig. 2b) and the tunnel depth was of about 3.3 m. In this way, the contour of the tunnel theoretically was comprised within the measurement profile. We used a unit (minimal) electrode spacing of 1 m and



48 electrodes, so the measurement profile was of 47 m length. We selected the WS array, which is an interesting compromise between the W and the DD arrays (Loke, 2016) offering a sufficient depth of investigation (about 9 m), a moderate noise level (Dahlin et al., 2004) and a sensitivity similar in horizontal and vertical directions. This latter point was of primordial importance since we were dealing with a ground with both a vertical stratification and a horizontal variation of resistivity due to the presence of the tunnel.

The WS technique consists of a symmetrical electrodes array. The potential electrodes (M and N) are placed in the middle with a spacing  $a$  and the current electrodes (A and B) at a distance of  $n \times a$  from the potential electrodes, where  $n$  is a positive integer. The unit spacing  $a$  is first kept constant while  $n$  is successively increased. Then,  $a$  is increased and kept constant again while  $n$  is successively increased. This procedure is reproduced until the maximum depth of investigation; depending on the maximum array length, is reached.

A WS sequence comprising 621 acquisition points (quadripoles) was programmed. It was composed of 9 values of  $a$ , from 1 m to 9 m, and 3 depth levels  $n$  for every value of  $a$ . Fig. 5 represents the position of the median depth of investigation of all the 621 acquisition points.

The acquisition points almost overlap vertically every three lines, which are thus characterized by a better resolution than the other lines. Comparison of the apparent resistivity of overlapping points is a good way of checking the robustness of the resistivity measure and the eventual effect of noise.

Two acquisitions were realized along the same profile: the first one (25 May 2017) under dry conditions (less than 1 mm of precipitation cumulated during the past week) and the second one (30 June 2017) under wet conditions (about 30 to 40 mm of precipitation cumulated during the past 3 days), both using the *Syscal Junior Switch 48* resistivity meter. The following injection parameters were used: impulsions of 500 ms, a constant reception voltage of 50 mV and a maximum injected voltage of 400 V. The number of stacks was between 4 and 10 with an objective coefficient of variation of 1%.

### 3. Resistivity models

#### 3.1. Apparent resistivity measurements

First of all, note that the measured apparent resistivity shows small coefficients of variation regardless of the depth of level and the position along the profile. Fig. 6 shows the coefficient of variation of every data point. The average coefficient of variation is of  $\approx 0.22\%$  under both wet and dry conditions, while the maximum coefficient of variation is of  $\approx 5\%$  and is obtained only in the first depth level. Moreover, only 4 stacks were necessary most of the time, what means that the measurement were relatively little noisy. Otherwise, no aberrant data points were found, so the measured apparent resistivity did not need to be filtered *a priori*.

In order to illustrate the major trends of the apparent resistivity, let us analyze the measurements along two perpendicular profiles: a vertical profile at mid tunnel span and a horizontal profile crossing at mid tunnel height. On both profiles, we calculated the average apparent resistivity corresponding to all the data points at a given level perpendicular to the profiles. Fig. 7a shows the results of the vertical profile corresponding to the evolution of the apparent resistivity in function of the median depth of investigation. Fig. 7b shows the results along the horizontal profile corresponding to the evolution of the apparent resistivity in function of the position of the potential electrodes center along the measurement profile.

The following points must be noticed concerning the vertical profile (Fig. 7a):

- Overall, the apparent resistivity increases with the depth, what is more visible under wet conditions than under dry conditions.
- Regardless of the water conditions, the smallest apparent resistivity is observed near the surface (silt layer) while the greatest resistivity is observed inside the tunnel, which is compatible with the resistivity estimated in Table 1.

- The top of the vault (masonry) matches the depth at which the difference between the wet and dry apparent resistivity is the smallest.
- The apparent resistivity slightly decreases near the top of the masonry (vault) after increasing again inside the tunnel atmosphere. This decrease is incompatible with the material resistivity estimated in Table 1. Indeed, the masonry is supposed to be more resistive than the backfill material above the tunnel.

The following points must be noticed concerning the horizontal profile (Fig. 7b):

- Overall, the apparent resistivity increases with the proximity to the tunnel, which is compatible with the resistivity of Table 1.
- However, there is a local decrease and then a local pic of the apparent resistivity near the tunnel boundaries that cannot be explained according to the resistivity of Table 1.

An explanation of the unexpected resistivity decrease near the masonry in both the vertical and horizontal directions will be proposed in Section 4.

## 3.2. Inverse resistivity model

### 3.2.1 Inversion method selection

Many distributions of the true ground resistivity can induce the same measured apparent resistivity; there is non-uniqueness of the solution. Inversion consists in determining one unique ground resistivity distribution in function of the apparent resistivity distribution. To do that, a model of ground resistivity distribution is postulated (homogeneous in general) and the apparent resistivity that would be obtained with such a distribution is calculated using finite element or finite difference method. The difference between the measured and calculated apparent resistivity is determined (RMS error). Then the model resistivity distribution is iteratively changed until the relative difference

between the calculated and measured apparent resistivity is lower than an objective RMS error value fixed arbitrary (in general from 1% to 5%).

The way the resistivity of the model is iteratively modified to fit the measured apparent resistivity depends on the chosen norm of inversion. There are 2 common norms (Loke, 2016): the smoothness constrained least-squares method (l2-norm) and the robust method (l1-norm, Claerbout & Muir, 1973), also based on the least-squares method. The robust inversion is supposed to be used where there is great resistivity contrasts over short distances. Such contrast was supposed to occur between the masonry ( $\approx 500 \Omega.m$ ) and the tunnel atmosphere ( $\infty$ ), so the robust method proposed by the RES2DINV software was selected.

Such as it is commonly recommended (Loke, 2016) the logarithm of the resistivity values was used instead of the resistivity itself for the results to be in a linear scale (instead of its natural logarithmic scale) which is more easily represented on the profiles.

To solve the (calculated) apparent resistivity in function of the resistivity model during inversion, we used the finite element method with a square mesh of constant size equal to the unit electrode spacing (1 m). Resistivity models were then composed of 481 blocks (Fig. 8).

### 3.2.2 Inversion of the unfiltered apparent resistivity

During inversion, the RMR error turned out to rapidly decrease over the iteration process. Seven iterations were sufficient to obtain an error of less than 1.5% in both wet and dry conditions, which matches the range typically recommended of 1% to 5% (Loke, 2015). The inversion results are presented in Fig. 8 with the position of the tunnel determined beforehand according to plans with an imprecision of less 0.5 m.

Note first that the inverse resistivity models under wet and dry conditions are qualitatively similar. There is no structure that we can detect only under a specific condition.

The ranges of resistivity expected for the investigated materials were effectively obtained. The inverted resistivity close to the surface in the silt layer ranges from 20  $\Omega\cdot\text{m}$  in zones where the soil was observed to be saturated of water to 200  $\Omega\cdot\text{m}$  in dry zones, which is around the expected average resistivity of about 100  $\Omega\cdot\text{m}$  (Table 1). The inverted resistivity of the backfill material under the silt layer is quite heterogeneous but ranges from 200 to 350  $\Omega\cdot\text{m}$  for an expected resistivity of 250  $\Omega\cdot\text{m}$  (Table 1). But surprisingly, the tunnel boundaries were not detected on the inverse models under both wet and dry conditions. Indeed, even if there was a higher resistivity of about 400  $\Omega\cdot\text{m}$  near the tunnel position that could match the resistivity expected for the tunnel masonry (500  $\Omega\cdot\text{m}$ , Table 1), the tunnel contours could not be clearly identified. Moreover, the expected highly resistive anomaly in the position of the tunnel center was not obtained. Such a highly resistive anomaly appeared horizontally aligned with the tunnel center, but it was not correctly positioned vertically and its size was lower than the tunnel size (dark red anomaly, Fig. 9).

### 3.2.3 Inversion of the filtered apparent resistivity

The measured apparent resistivity was not initially filtered because no aberrant data were visible and the data point's coefficients of variation were small. However, the data show large differences between two successive points. We supposed that this scattering, which was not considered as an artifact *a priori*, was at the origin of the non-detection of the tunnel with the inverse models. Therefore, we applied to the measured apparent resistivity the automatic average median filter followed by the automatic sliding mean filter proposed by the PROSYSII software (Iris Instrument, France). These filters consist in smoothing the measured apparent resistivity horizontally, i.e. along the lines corresponding to every depth levels successively, by changing the resistivity of every data point to be equal to the median and the arithmetic mean of the neighbor data points respectively. The neighbor data points used for the smoothing were selected within a distance of  $1 \times AM$  around the considered data point for the sliding median and  $0.5 \times AM$  around the considered data point for

the sliding average (PROSYSII software recommendation), where  $AM$  is the distance between the closest injection (A) and potential electrodes (M).

The resulting apparent resistivity is vertically similar but horizontally smoother than the unfiltered one (Fig. 10b). It keeps the overall same trends except that the pics of resistivity observed at positions of 13 m and 37 m were significantly smoothed (Fig. 10b).

On the image obtained after inversion (Fig. 11), it is surprising to see that the main tunnel now clearly appears as one anomaly of low resistivity ( $\approx 70 \Omega.m$ ) in comparison with the surrounding material (300 to 400  $\Omega.m$ ) while there is still a high apparent resistivity at the tunnel position (Fig. 10b). The tunnel boundaries now are detected with a relatively good precision both in the vertical and horizontal directions. Indeed, the top of the anomaly coincides with the top of the vault, the center of the low resistivity anomaly nearly is in the center of the tunnel and the size of the anomaly is of the same order as the tunnel width.

Note that the water condition has no significant effect on the main tunnel detection. However, under wet conditions (Fig. 11a), a low resistivity anomaly of smaller size appears at  $x \approx 36$  m. This anomaly is adequately positioned (correct side compared to the main tunnel and correct altitude) to be interpreted as the effect of the small secondary tunnel whose precise position is actually unknown. However, the fact that this anomaly does not appear under dry conditions (Fig. 11b) could invalidate this interpretation.

Sections 4.1 and 4.2 will respectively discuss the origin of the low resistivity anomaly at the main tunnel position and the effect of the smoothing filter on the detection of this anomaly. The possible detection of the small secondary tunnel under wet conditions will be discussed in section 4.3.

## **4. Discussion of the results**

### **4.1 Detection of the main tunnel**

#### 4.1.1 Preliminary assumptions

As expected, the covered stream tunnel can be successfully detected using the 2D-ERT technique. But surprisingly, the tunnel is detected as a low resistivity anomaly instead of a high resistivity anomaly on the inversed models. A high resistivity anomaly would have been easily explained by the very high resistivity of the tunnel's atmosphere compared to the surrounding materials, which is not in doubt. Conversely, explaining the low resistivity anomaly is not immediate especially since a high resistivity anomaly does appear on the apparent resistivity profile but disappears after inversion. According to Putiska et al. (2012) such low resistivity anomaly can be explained by the presence of a thin layer of relatively conductive material around the tunnel that would deform the resistivity image after inversion. This layer can be composed of water, moisture and clay particles deposited by seepage water. The effect of such a layer was demonstrated by the authors according to synthetic forward resistivity models considering circular cavities without masonry. They showed that the ratio of the thin conductive layer resistivity to the surrounding soil resistivity has to be of at least 0.1 for the cavity to be properly detected.

In order to verify the validity of Putiska's results in the case of the old masonry tunnels we were studying, forward resistivity models were conducted with the RES2DMOD software (Loke, 2014). Forward resistivity modelling aims to evaluate the apparent resistivity that would be measured and the inverse resistivity model that would be obtained with it considering a given "true" ground resistivity distribution (resistivity model) and a given electrode array.

#### 4.1.2 Forward modelling considering a uniform surrounding

We constructed a resistivity model with tunnel geometry as close as possible from the true tunnel geometry. However, we considered an intentionally simplistic geometry of the surrounding materials

(Fig. 12). The objective was first to evaluate the detectability of the tunnel as a low resistivity anomaly where it is surrounded by a homogenous and uniform material.

To do so, the resistivity of the backfill, the rock and the masonry was fixed according to Table 1 and the resistivity of the atmosphere was fixed at 100 000  $\Omega\cdot\text{m}$  (infinite relatively to the other materials). The resistivity of the thin conductive layer around the masonry was logarithmically varied from 0.01 to 10  $\Omega\cdot\text{m}$ . The voltage that would be measured with a WS array at the surface and a unit electrode spacing of 1 m was calculated, as well as the apparent resistivity, with the RES2DMOD software. Then the measured apparent resistivity was inverted with the RES2DINV software considering the settings described in section 3.2.1.

The obtained inverse resistivity model was compared to that obtained considering the field measurement (section 3.2.3) along two profiles: a vertical line crossing the tunnel at mid-span and a horizontal line crossing the tunnel at mid-height. The results are synthetized in Fig. 13.

With no conductive layer, the tunnel appears as a highly resistive anomaly. With a thin conductive layer of 10  $\Omega\cdot\text{m}$  resistivity, the tunnel is detected as an anomaly of slightly higher resistivity than the surroundings (red curves) in both the horizontal (Fig. 13a) and vertical directions (Fig. 13b). With a thin layer resistivity lower than 1  $\Omega\cdot\text{m}$ , the tunnel is detected as an anomaly of lower resistivity than the surroundings. The ratio of the thin layer resistivity to the surroundings resistivity for the tunnel to be detected as a low resistivity anomaly therefore is of about 0.004. But for the low resistivity anomaly to be of the same order as that obtained considering the field measurements ( $\approx 70 \Omega\cdot\text{m}$ ), the thin layer resistivity has to be in the range of 0.01 to 0.1  $\Omega\cdot\text{m}$ . The corresponding resistivity ratio is of about 0.0002. This ratio cannot be directly compared to that proposed by Putiška et al. (2012) since the model geometry was different. Nevertheless, the description of the effect of a thin conductive layer around the tunnel such as proposed by Putiška et al. (2012) is qualitatively verified here.

#### 4.1.3 Forward modelling considering a more realistic surrounding



381 Despite the good agreement between the resistivity obtained at the tunnel position after inversion of  
382 the measured and modelled apparent resistivity, the resistivity obtained outside the tunnel did not  
383 fit well the expected resistivity horizontally (Fig. 13a) or vertically (Fig. 13b). This was probably due to  
384 the simplistic flat geometry we considered for the rock under the tunnel. Actually, the tunnel was  
385 built inside an incised valley, so the rock is supposed to form slopes on both sides of the tunnel. The  
386 exact slope is unknown since the rock is fully covered by backfill materials, and it is probably not a  
387 regular slope. However, in order to simply take it into account in the forward models, we considered  
388 a regular slope of alternatively 20°, 45° and 70° (the model with a slope angle of 70° is presented in  
389 Fig. 14). The resistivity of the thin conductive layer was fixed at 0.01  $\Omega$ .m.

390 Once again, the obtained inverse resistivity model was compared to that obtained considering the  
391 field measurement (section 3.2.3) along two profiles: a vertical line crossing the tunnel at mid-span  
392 and a horizontal line crossing the tunnel at mid-height. The results are synthetized in Fig. 15.

393 Along the horizontal profile (Fig. 15a) increasing the rock slope has several consequences. First, the  
394 resistivity from the forward models inside and outside of the tunnel fits better the resistivity from  
395 the measured apparent resistivity. Secondly, the resistivity decrease near the tunnel boundary is  
396 steeper and closer to that obtained with the measured apparent resistivity. Thirdly, however, the  
397 limits of the anomaly are in a less good agreement with the inverted resistivity obtained considering  
398 the field measurements: the size of the tunnel is overestimated.

399 Along the vertical profile (Fig. 15b) increasing the rock slope has less consequence. Due to adding a  
400 layer of low resistivity material representing a silt layer at the surface, the resistivity curve near the  
401 top of the vault has a shape that is more similar to the expected shape. However, the intensity of the  
402 resistivity does not fit the expected intensity better.

403 Overall, the presence of a rock slope besides the tunnel boundaries increases the intensity of the  
404 lowly resistive anomaly compared to the surroundings after inversion of the apparent resistivity.

Still, the forward models we conducted did not explain why we needed to smooth the measured apparent resistivity by applying sliding filters to be able to detect the tunnel on the image obtained after inversion. Justifications of that point are provided in the next section.

#### 4.2 The effect of the smoothing filter

The main tunnel only was detected after the apparent resistivity was smoothed according to a sliding average and a sliding median filter. One could have thought that the measured apparent resistivity was submitted to noise, which was attenuated thanks to the smoothing filter. But the fact that this observation was similarly made on both sides of the tunnel and considering two separate acquisitions, under wet and dry conditions, realized one month apart, shows that this is probably not due to a random noise.

The main difference between the filtered and the unfiltered apparent resistivity that appears on the horizontal profile (comparison of Figs. 7b and 10b) is the smoothing of the pic of resistivity besides the tunnel lateral boundaries (at 13 m and 37 m along the horizontal profile). So the following explanation can be proposed.

Without applying the smoothing filter, no clear highly resistivity anomaly was visible at the tunnel position because of the presence of pics of resistivity a few meters beside the tunnel boundaries. Consequently the tunnel contours cannot be precisely viewed on the inversion image.

There was no clear low resistivity anomaly neither because the effect of the thin conductive layer, which is visible on the apparent resistivity profile (at positions of 14 m and 35 m in Fig. 7b), disappears after inversion. It is probably due to the fact that the effect of the conductive layer significantly affects the apparent resistivity over a too short horizontal distance to induce a resistivity decrease during the least square inversion process.

Conversely, after applying the smoothing filter, the pics of resistivity a few meters beside the tunnel boundaries disappear and the presence of the thin conductive layer now is fictively characterized by

an approximately constant apparent resistivity beside the tunnel boundaries (contoured zones in Fig. 7b). The effect of the thin conductive layer is significant, in this case, over a sufficient distance so that it forces the least square process to decrease the resistivity at the tunnel position for the calculated apparent resistivity to fit the measured apparent resistivity.

We have no direct measurement of what can induce the pics of apparent resistivity. However, we can reasonably make the following supposition.

It was occasionally observed on various covered stream tunnels that a layer of thin backfill material mostly composed a coal particles was deposited around the masonry before the deposit of a progressively coarser backfill material up to the final altitude. Such a construction method was probably used to assure a uniform loading of the vault. The presence of a layer of backfill material mostly composed of coal near the masonry with a relatively high resistivity of about 3000  $\Omega \cdot m$  (we estimated it thanks to a small scale *in situ* measurement) compared to the surroundings could be responsible for the pic of resistivity observed in the horizontal profile of apparent resistivity (Fig. 7b).

#### 4.3 Detection of the small secondary tunnel

A small anomaly of low resistivity, which can be interpreted as the presence of the small secondary tunnel, appears on the inversion image under wet conditions only (Fig. 11a). Because the main tunnel was demonstrated to be detectable under both wet and dry condition, we suppose that the small anomaly of low resistivity is, this time, probably not due to the presence of a thin conductive layer around the small tunnel. But the presence of the highly resistive tunnel atmosphere should at least induce a highly resistive anomaly at the small tunnel position, which is not observed either. So, we came to the following conclusions.

The small secondary tunnel is probably partially collapsed. Under dry conditions, the resistivity contrast between the tunnel and the surrounding soil therefore is probably too low to be detected.

But under wet conditions, the small secondary tunnel probably is a preferential flow path due to its

very shallow depth (less than 2 m). So its resistivity probably decreases due to the presence of water, making it detectable with 2D-ERT.

## 5. Conclusions

In general, the presence of subsurface cavities is expected to be detected as a highly resistive anomaly on 2D-ERT profiles because of the very high (say infinite) resistivity of the cavity atmosphere. But according to the results we obtained while conducting 2D-ERT profiles above an old masonry tunnel of known position, cavities can also be detected as low resistivity anomalies or eventually undetected under certain conditions. Anomalies of low resistivity on the inverse resistivity section can be due to the presence of a thin conductive layer around the tunnel induced by the presence of moisture and seepage water deposits. This effect was demonstrated based on forward resistivity models performed by Putiška et al. (2012). In this study, we confirmed this effect based on *in situ* resistivity measurements.

According to the obtained results, three situations can be encountered:

- If the tunnel has no conductive layer around the masonry, it will appear as a highly resistive anomaly after inversion of the apparent resistivity.
- If the tunnel masonry is in contact with a thin layer of very low transversal resistivity compared to the surroundings, it will appear as low resistivity anomaly after inversion of the apparent resistivity provided that an adequate electrode array and inversion method are selected.
- If the tunnel is surrounded by a highly resistive material, it will not be unconditionally detected even in the presence of a conductive layer in contact with the masonry.

In this study, we encountered the third situation: a highly resistive anomaly was observable at the tunnel position on the apparent resistivity profiles but it could not be properly detected on the inversed resistivity image. The problem was solved by filtering the measured apparent resistivity with

a sliding median and a sliding average whose smoothing distance increases with the depth level. But after filtering, the inverse resistivity image showed a low resistivity anomaly at the precise tunnel position instead of an expected highly resistive anomaly. The detection of the considered tunnel was successful, but there is no evidence that this method can be generalized. In addition, this is probably not a satisfying option to modify the apparent resistivity by applying a filter while it did not need to be filtered *a priori*.

Otherwise, the detection of a small secondary tunnel, of which we did not know the precise location *a priori*, turned out to be possible only under wet conditions (after several days on moderate rain), which is probably due a partial collapse of the tunnel.

Overall, the detection of old masonry tunnels with the 2D-ERT technique associated to the classical least-squares method of inversion (l1-norm here) turns out to be a complex problem that can be due to both the measured apparent resistivity and/or the inversion process. Further studies should therefore be conducted in order to better constrain the detectability conditions of old masonry tunnels using 2D-ERT, which is nevertheless a technique with many advantages.

## **Acknowledgements**

We would like to thank BpiFrance, the European Union (FEDER-FSE program) and *la region Occitanie* for the financial support of the research project FUI 22 EREDOS n°LR0012285. We are also grateful to Dr. David Salze for the project coordination, to Mr. Thibault Jeannin for material assistance and to Mr. Henri Chalvidan and the municipality of Robiac-Rochessadoules for their collaboration.

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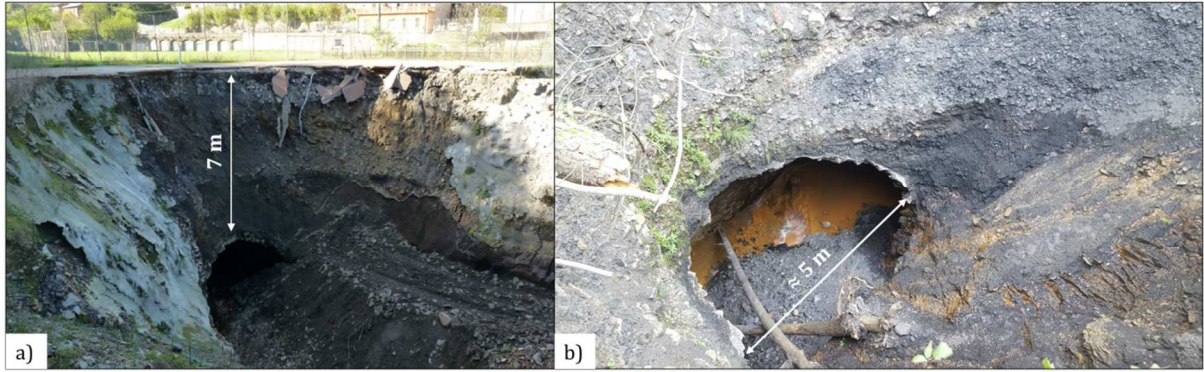
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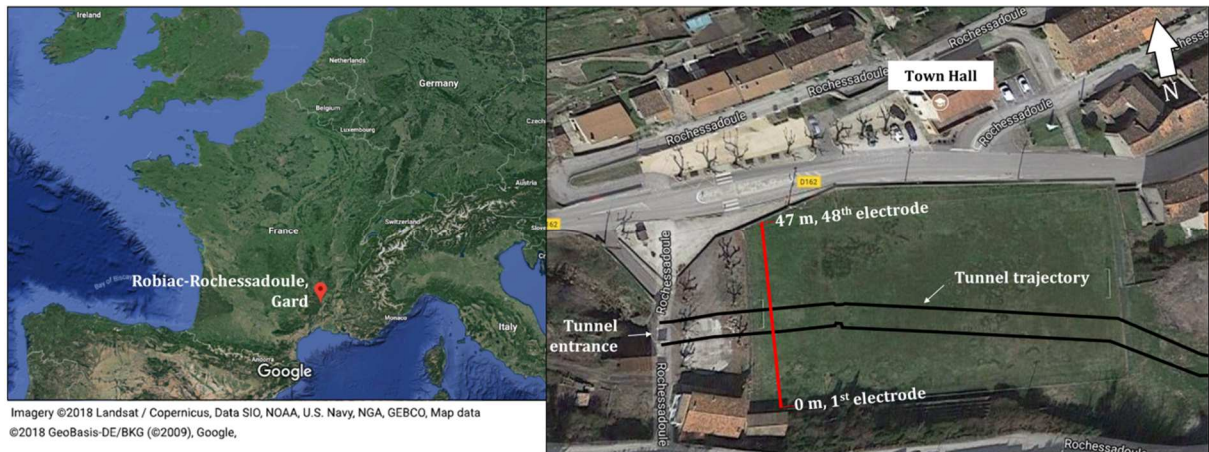
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**Fig. 1:** a) Photograph of a  $\approx 25$  m diameter sudden collapse occurred in 2012 in Robiac-Rochessadoule (Gard, France, picture by Levesque, 2014). b) Photograph of a large collapsed sinkhole ( $\approx 20$  m height) occurred at an indeterminate date in La Grand-Combe (Gard, France, photographed during summer 2017).



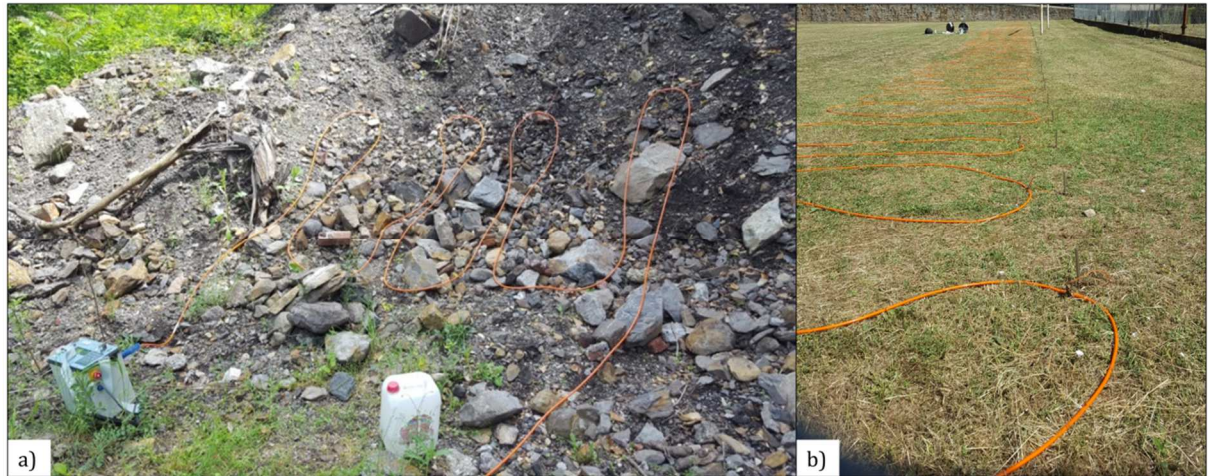
**Fig. 2:** Study site and ERT profile location.



**Fig. 3:** Photographs of the entrance of the Rochessadoule covered stream tunnel (Robiac-Rochessadoule, Gard, France, taken during summer 2017): a) from the outside and b) from the inside.



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**Fig. 4:** a) 4-electrodes array used for the measurement of the *in situ* resistivity of a pile of coal mine tailings

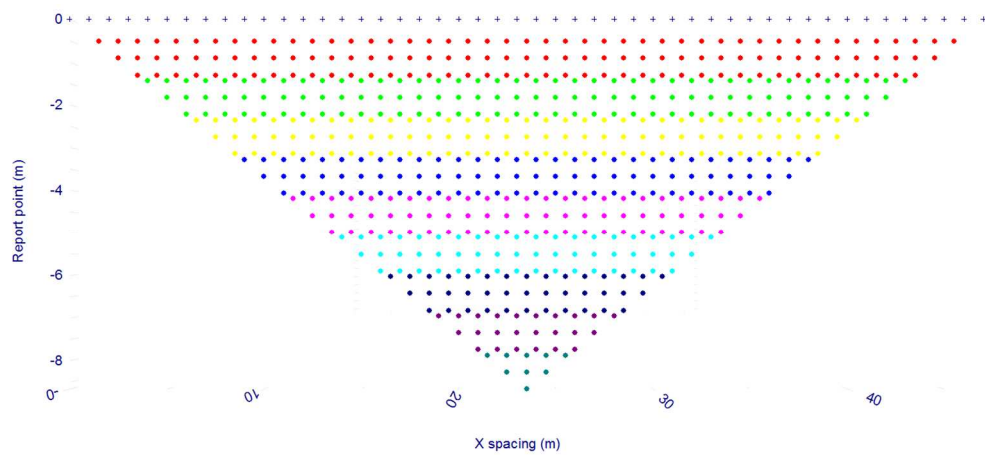
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located near the studied tunnel, b) 48-electrodes array used for the measurement of the apparent resistivity of

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the ground above the studied covered stream tunnel.

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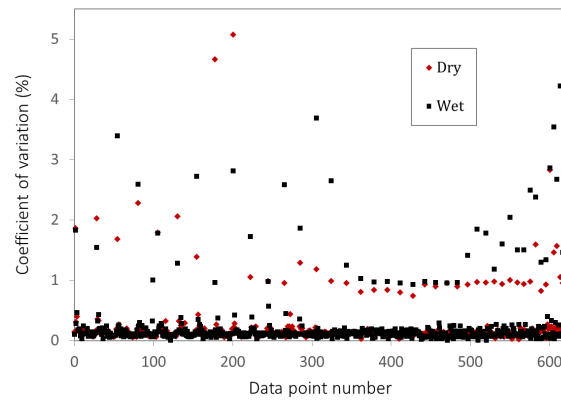
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**Fig. 5:** Data points position of the ERT profiles. The position along the x axis represents the center of the

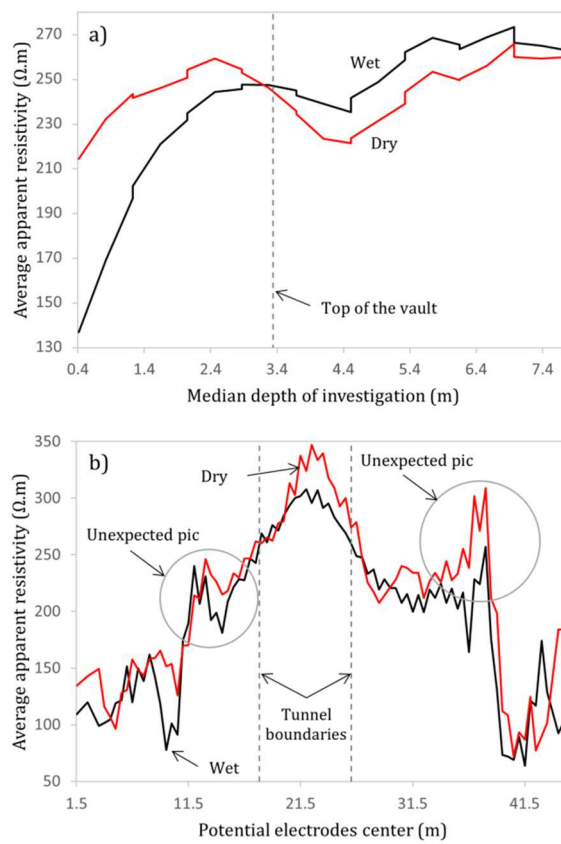
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quadripoles while the position along the y axis represents the median depth of investigation.

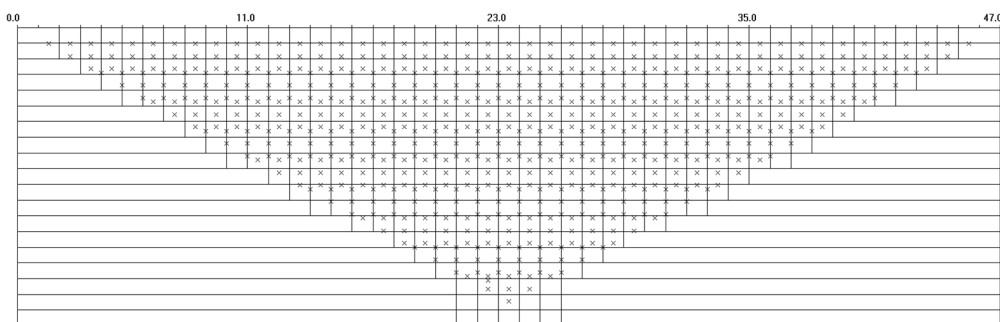
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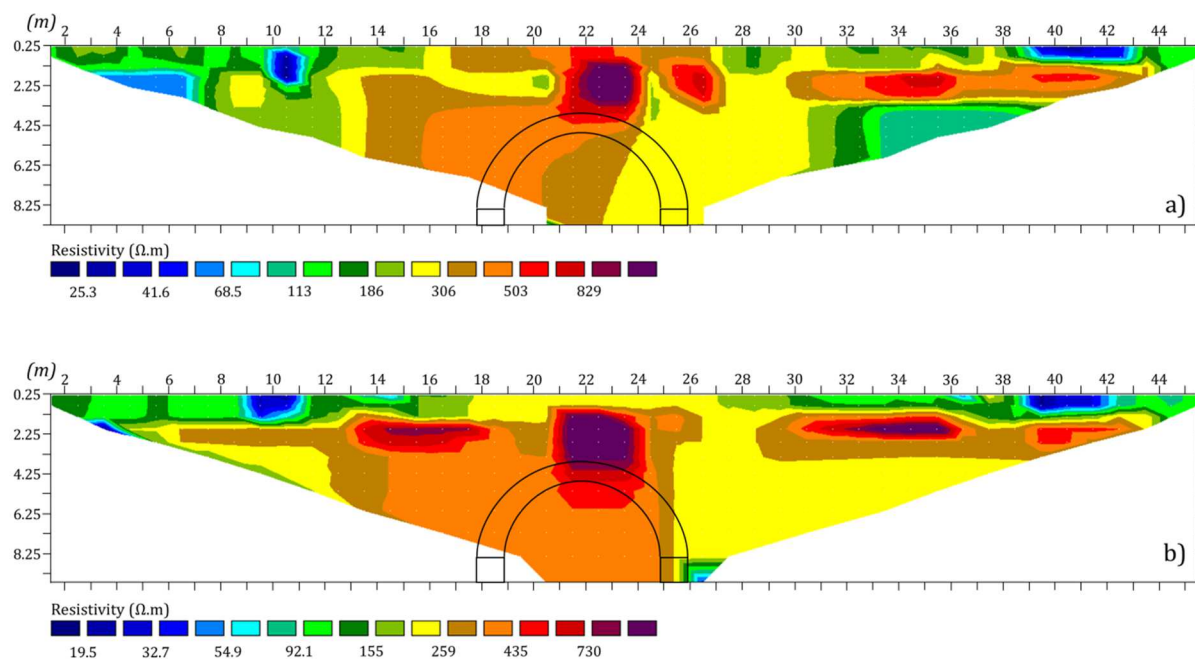
**Fig. 6:** Coefficient of variation of the measured apparent resistivity considering the successive stacks performed for every data point (quadripole).



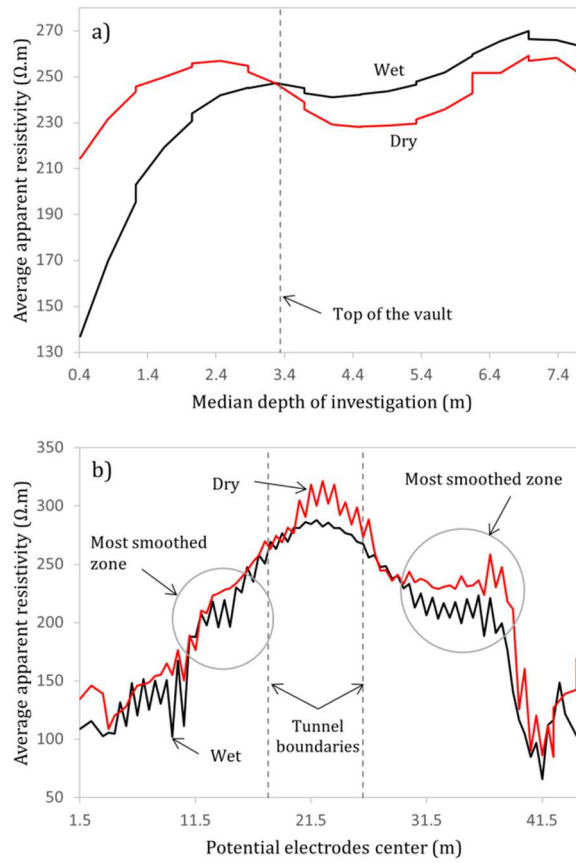
**Fig. 7:** Evolution of the averaged measured apparent resistivity in function of a) the median depth of investigation and b) the potential electrodes center.



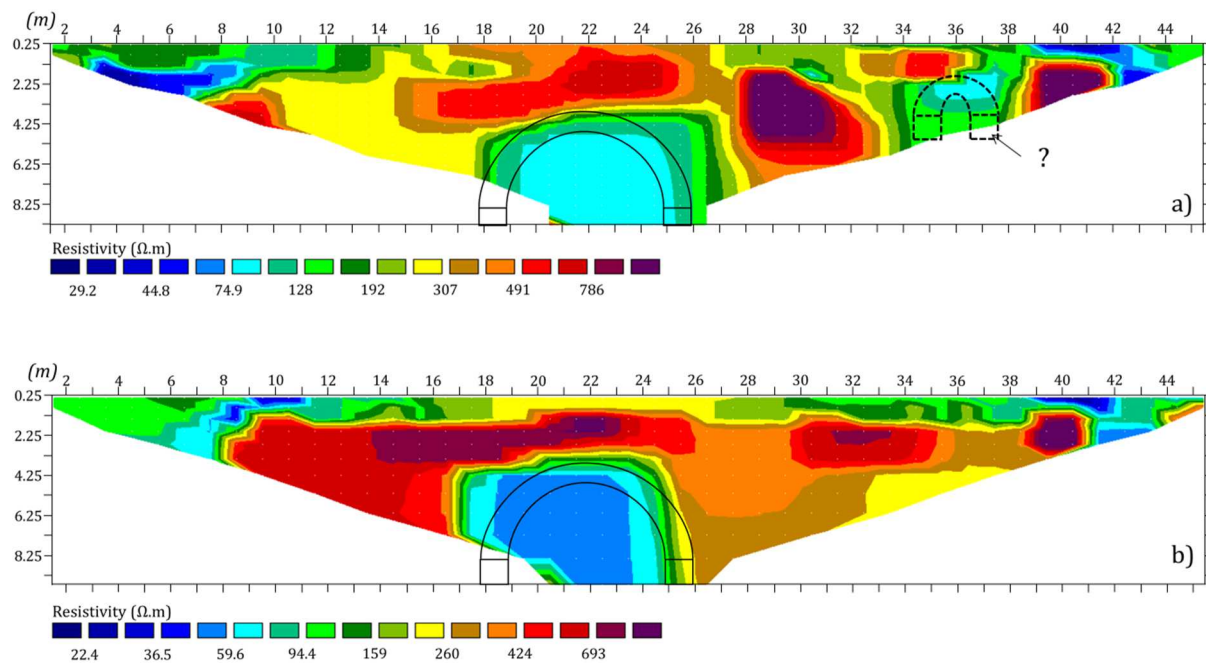
**Fig. 8:** RES2DINV grid of the finite element model considered for the inversion process.



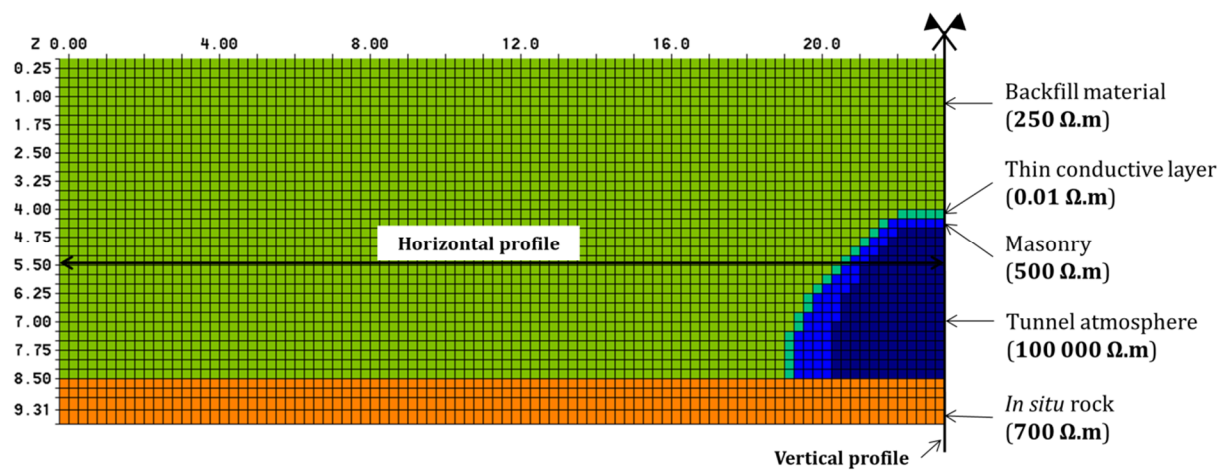
**Fig. 9:** Inverse resistivity model of the measured apparent resistivity under a) wet and b) dry conditions. The tunnel's position is indicated on the profiles.



**Fig. 10:** Evolution of the averaged apparent resistivity after application of a smoothing filter in function of a) the median depth of investigation and b) the potential electrodes center.

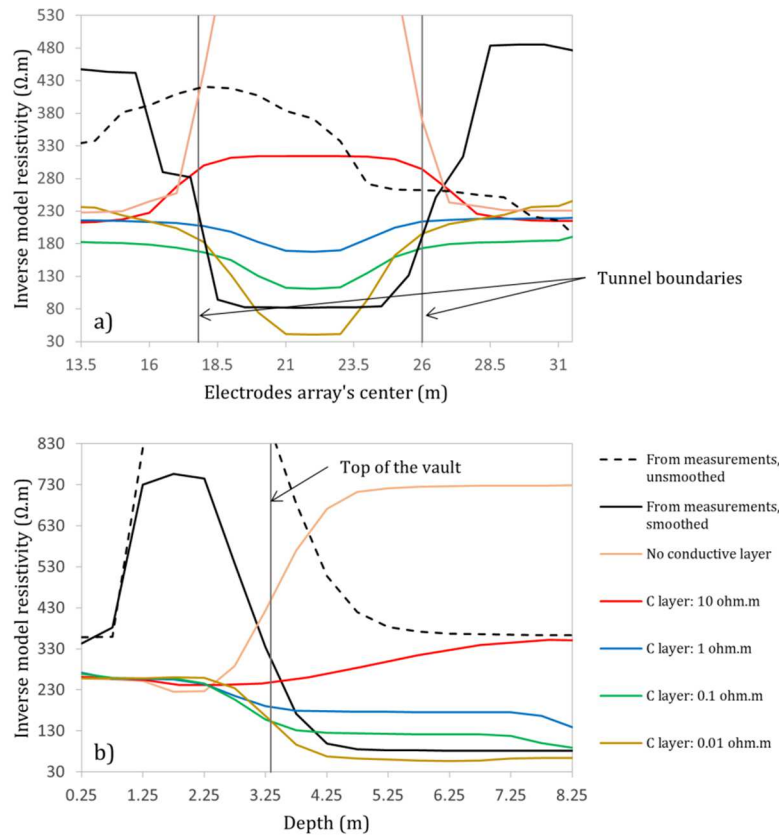


**Fig. 11:** Inverse resistivity model of the filtered (smoothed) apparent resistivity under a) wet and b) dry conditions. The main tunnel's position is indicated on the profiles and a position for the small secondary tunnel is supposed in case a).

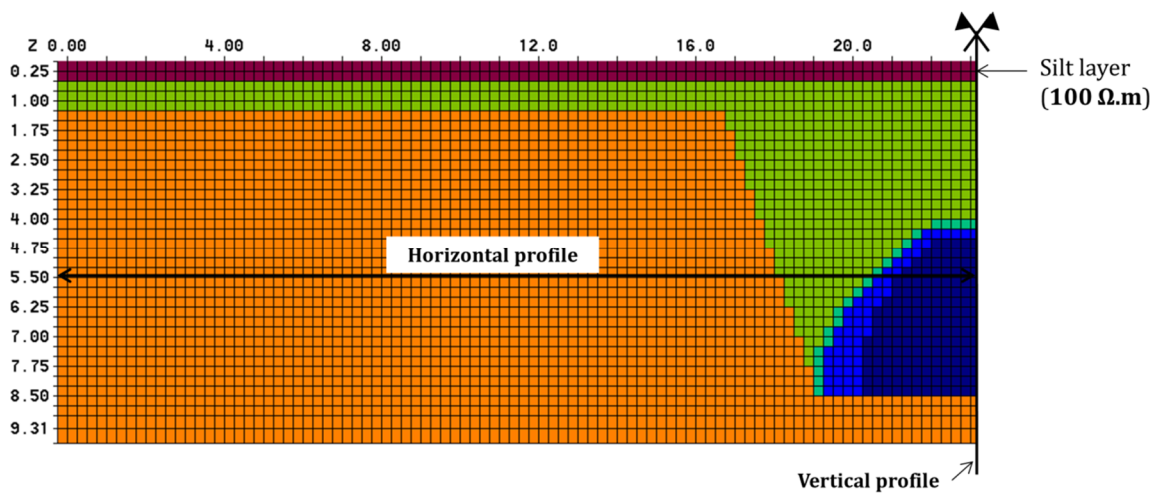


**Fig. 12:** Geometry of the first synthetic model (RES2DMOD).

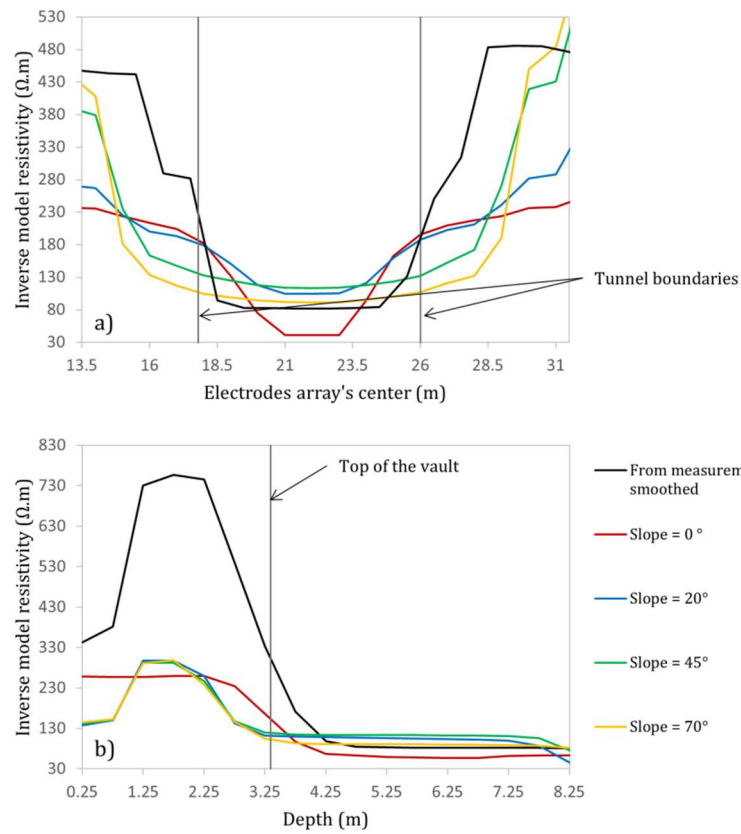




**Fig. 13:** Comparison of the inverse model resistivity obtained considering the field measurements (averaging the wet and dry resistivity, black curves) and considering the synthetic (RES2DMOD) models (color curves) with a variable resistivity of the thin conductive layer, a) along a horizontal profile at mid-height of the tunnel and b) along a vertical profile at mid-span of the tunnel.



**Fig. 14:** Geometry of the second synthetic model (RES2DMOD).



**Fig. 15:** Comparison of the inverse model resistivity obtained considering the field measurements (averaging the wet and dry resistivity, black curve) and considering the synthetic (RES2DMOD) models (color curves) with a variable rock slope angle, a) along a horizontal profile at mid-height of the tunnel and b) along a vertical profile at mid-span of the tunnel.