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The MYG methodology to carry out 3D electrical resistivity tomography on media covered by vulnerable surfaces of artistic value

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Shortened title: **The MYG method for 3D ERT on media with surfaces of artistic value**

Summary. – The Electrical Resistivity Tomography (ERT) is still not frequently used for the study of walls, floors and foundations of buildings of artistic value, like Ground Penetrating Radar (GPR) or other commoner techniques, although it exhibits great potentiality in terms of resolution power. The main limitation for the applicability of ERT in the Cultural Heritage field arises from the method of current injection: often it is necessary to drive current electrodes into small perforations on the acquisition surface in order to allow a current flow sufficient to obtain a good signal to noise ratio. To overcome this limitation the Maximum Yield Grid (MYG) methodology has been developed, in which only a small fraction (about 1/15) of the electrodes of the acquisition grid is used for current injection, also with a significant reduction of the acquisition time. Two cases of study on media covered by precious mosaics are presented, the first one referred to the main wall of the fountain hall of the Zisa palace of Palermo and the other one about the ambulatory of the "Villa Romana del Casale" of Piazza Armerina.

PACS 93.85.Jk - Geophysical observations, instrumentation and techniques: Electrical methods
PACS 91.25.Qi - Geoelectricity

1. – Introduction

During the last decades geophysics has considerably broadened its field of application, with great efforts spent in adapting methodologies to smaller scale problems: from the classical employments, like the study of earth structure, seismology and petroleum and mineral exploration, nowadays it is common to apply geophysical techniques to environmental, engineering and archaeological problems at shallow depths. Furthermore the low invasivity of geophysical methodologies (that usually reconstruct the inside structures of the studied media only with measurements from their surfaces) has allowed their increasing diffusion in the Cultural Heritage field. In this contest the Electrical Resistivity Tomography (ERT) is still not frequently used for the study of walls and foundations of buildings of artistic value, like Ground Penetrating Radar (GPR) or other commoner techniques, although it exhibits great potentiality in terms of resolution power. In fact by 3D ERT it is possible to reconstruct the tridimensional distribution of the resistivity of the interior of the investigated medium only from measurements on the surface, and the knowledge of the resistivity distribution could give interesting insights into the constitutive structure of buildings. In fact in the almost entirety of construction materials (like stones, bricks, mortar, concrete, plaster) and foundation soils of ancient buildings the electrical conduction is electrolytic rather than electronic, and depends on the conductivity of the water solution contained in the materials, on the porosity of materials and on their saturation level. Hence the knowledge of the resistivity (or conductivity) distribution inside walls, floors or foundation soil of a building can reveal the presence of different construction materials (because of differences in porosity), the moisture content and/or the preferential paths of infiltration of water and the presence of voids.

A typical geoelectrical measurement is performed by means of four electrode in contact with the observed medium: two electrodes are used to inject and measure DC current and the other two are used to measure the potential drop caused by the current flow. The measurement is carried out with direct and reverse direction of current flow: the difference of potential measures eliminates the spontaneous potential difference present between the potential electrodes; the resulting values of measured potential drop and injected current are linked by the Ohm’s law.

One geoelectrical measurement is sufficient to calculate the resistivity distribution of the medium only in presence of an isotropic and homogeneous medium, otherwise it is necessary to build an appropriate sequence of quadrupolar measurements that contain adequate information for the tomographic reconstruction of the resistivity distribution. For 3D investigations the sequence is constructed selecting quadrupoles among an acquisition grid of electrodes placed on the surface of the studied medium (often the grid is a N X M rectangle of equidistant electrodes).

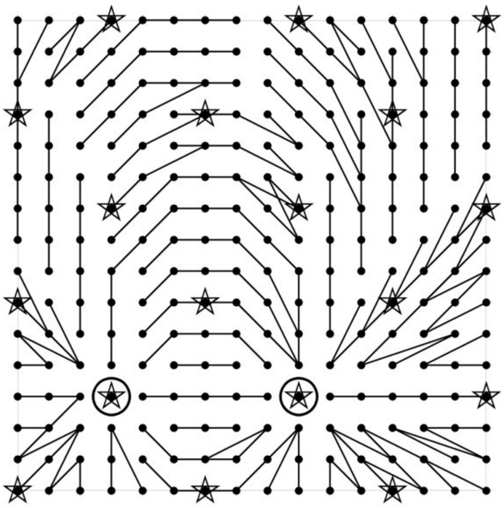
The main limitation for the applicability of ERT in the Cultural Heritage field arises from the method of current injection: often it is necessary to drive current electrodes into small perforations on the acquisition surface in order to allow a current flow sufficient to obtain a good signal to noise ratio. In fact in geoelectrical measurements the contact resistance between the electrodes and the medium is usually greater (sometimes several order of magnitude greater) than the resistance of the medium itself, and the insertion of the electrodes inside the medium significantly decreases the contact resistance and enhances the current flow (contact area between electrode and medium and potential difference between electrodes being equal). Instead the electrodes used for potential measurements could be only in contact with the acquisition surface if the input impedance of the instrument is sufficiently high (typically greater than 100 MOhm): for instance flat electrodes [1] or electrocardiogram (ECG) electrodes [2] can be used. However the classical sequences of quadrupolar measures, like the Dipole-Dipole one or the Wenner-Schlumberger one, use all the electrodes of the acquisition grid for current injection, and then the invasivity of the investigation could be significant on precious and vulnerable surfaces, considering that usually hundreds of electrodes are used.

To overcome this limitation the Maximum Yield Grid (MYG) methodology has been developed [3], in which only a small fraction (about 1/15) of the electrodes of the acquisition grid is used for current injection, also with a significant reduction of the acquisition time (typically 40 times smaller than that of the fastest classical sequence for a 16 X 16 acquisition grid, resolution power being equivalent).

In this paper two cases of study on media covered by precious mosaics are presented, the first one referred to the main wall of the fountain hall of the Zisa palace of Palermo and the other about the ambulatory of the Villa Romana del Casale of Piazza Armerina.

2. – The MYG methodology

The MYG methodology has been developed in order to minimize the number of electrodes of the acquisition grid used for current injection, maintaining the resolution power of the methodology equivalent to those of the better classical sequences of measures. With an acquisition grid of N electrodes, for each current injection between two of them, all the remaining N-2 electrodes are used for potential measurements. On the contrary, with classical sequences, only few electrodes (typically two, at most about ten) are used to measure potential differences. The huge increase of potential measurements per injection current allows the significant reduction of the number of current injections (and then of current electrodes) necessary to obtain a good resolution power. Simulations on synthetic models have been carried out to assess resolution in comparison to classical sequences of measures [3]. For each current injection the potential dipoles are selected as close as possible to the current lines, in order to maximize the signal to noise ratio. Figure 1 presents a regular 16 X 16 acquisition grid, with a typical set of current electrodes and the potential dipoles selected for a specific current dipole. The choice of the current electrodes and current dipoles is not critical in the determination of the resolution capability of the MYG methodology: different sets of current



electrodes uniformly distributed in the acquisition grid (the number of electrodes, about 1/15 of the total, being equivalent) or small variations of the positions give similar results.

Figure 1. Black dots: potential electrodes of the acquisition grid; stars: current electrodes of the acquisition grid; black lines: potential dipoles for the current dipole indicated by the black circles.

3. – Data acquisition and interpretation method

In both the field tests presented in this paper the MRS256 instrument (GF Instruments, Czech Republic) has been used. This instrument is composed by two distinct modules, one for current injection and the other one for potentials measure, connected together for synchronization and with a laptop that manages measurements. The potential module handles up to 256 channels in simultaneous acquisition: the electrodes are connected to the potential module by multichannel cables. The analog to digital conversion is performed with a 22bits converter (5 Volts range) and the input impedance of the conditioning circuit is 10 GOhm for each channel; self potentials and linear drifts are automatically removed from resistance measures by means of repetition of measures with inversion of the current flow. At least four repetitions for each resistance measure were carried out. The current module can apply up to 560 Volts between current electrodes: lower voltages were applied in the field (typically 140 or 280 Volts) when the potentials at the measuring electrodes imposed by the current flow exceeded the measure range.

The MRS256 instrument measures the voltage differences between each electrode of the acquisition grid and one reference electrode. The estimation of the resistances for quadrupoles following the current lines, as required by the MYG method, is a simple linear algebraic calculus performed in data analysis. The calculus is carried out by a specific software developed to automatically calculate the sequence of potential dipoles and to reject noise data.

The reconstruction of the resistivity distribution from the set of quadrupolar measures is a typical geophysical inversion problem, nonlinear and ill-posed. The first step in the inversion procedure is the definition of an algorithm for the solution of the forward problem, that calculates the resistance values for an acquisition sequence with the resistivity distribution as input data. The forward problem in 3D geoelectrical tomography is normally solved subdividing the studied volume in voxels (with homogeneous resistivity in their interior) and applying finite difference or finite element approximations of the differential equations governing the current flow. The finite difference method ([4],[5]) solves a linear approximation of the differential equation of the charge conservation in a medium in which Ohm's law is valid. The finite element method solves the forward problem minimizing the total energy of the electrical field on the discretized volume ([6],[7]). The inversion process uses the forward algorithm to iteratively minimizes both the discrepancy between observed and calculated data and the spatial variations of the resistivity distribution ([8],[9],[10]), in order to avoid oscillations in the resistivity distribution due to the nature of the ill-posed inverse geo-electrical problem.

The RES3DINV commercial software (Geotomo Software) performs the entire inversion process for geoelectrical measures and has been used to interpret the data presented in this paper. Standard inversion parameters of the software have been used and the inversion models of the two cases do not present significant variations when changing the inversion parameters of the software (for instance selecting finite difference or finite element forward method).

4. – The fountain hall of the Zisa palace (Palermo, Italy)

The Zisa Palace (XII century A.D., figure 2) is an ancient building of Palermo built by Arabian craftsmen for king William I of Sicily and used as summer residence by the Norman kings. The fountain hall of the palace presents the main wall covered by a precious mosaic that suffered a detachment phenomenon because of the moisture presence inside the wall. During the restoration process of the mosaic a 3D ERT by means of the MYG methodology was carried out, in order to try to explain the source of the moisture. The mosaic is about 3.5m above the floor of the hall, and then the provenience of moisture from the subsoil was improbable; for this reason the ERT investigation was executed on the mosaic. A regular grid of 11 X 16 adhesive ECG electrodes, 2m high and 3m wide, was placed on the mosaic for voltage measurements; 15 small nails (2mm wide) were inserted in small perforations among the tesserae of the mosaic for current injection. Small amounts of water and conductive gel were injected into the perforations before the nails insertion to enhance the electrolytic conduction around the electrodes, and consequently the current flow. Figure 3 presents the positions of potential and current electrodes superimposed on a picture of the mosaic, while figure 4 shows a typical drilled perforation among the mosaic tesserae.

Figure 2. The Zisa palace (Palermo, XII century A.D.)

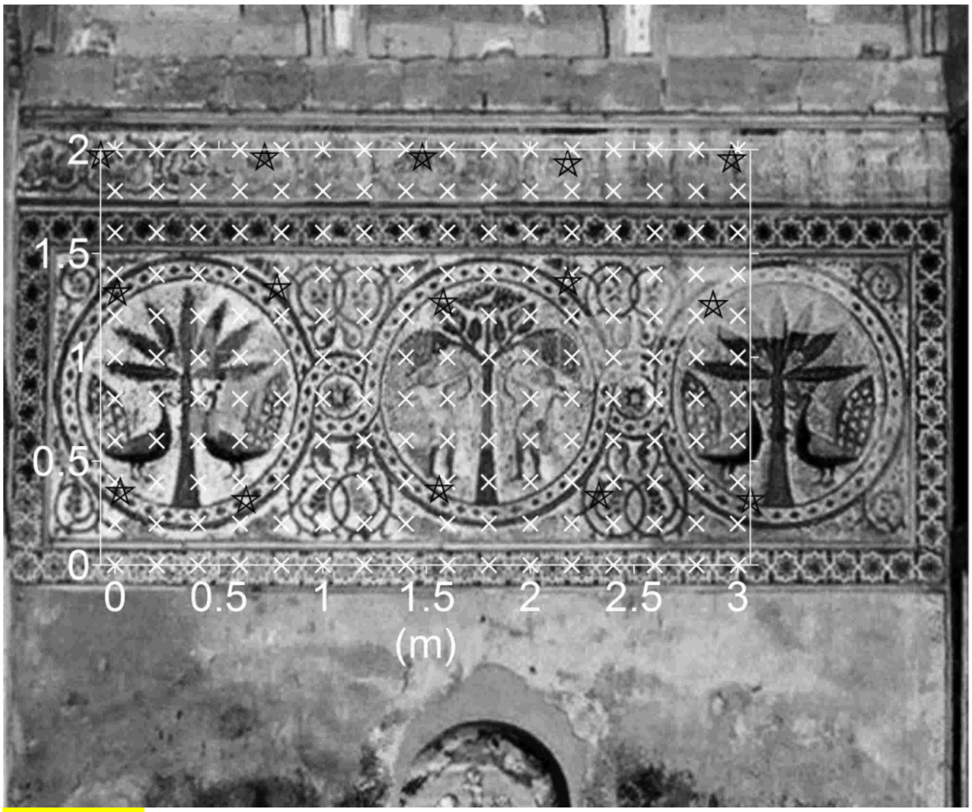


Figure 3. White crosses: potential electrodes; black stars: current electrodes.

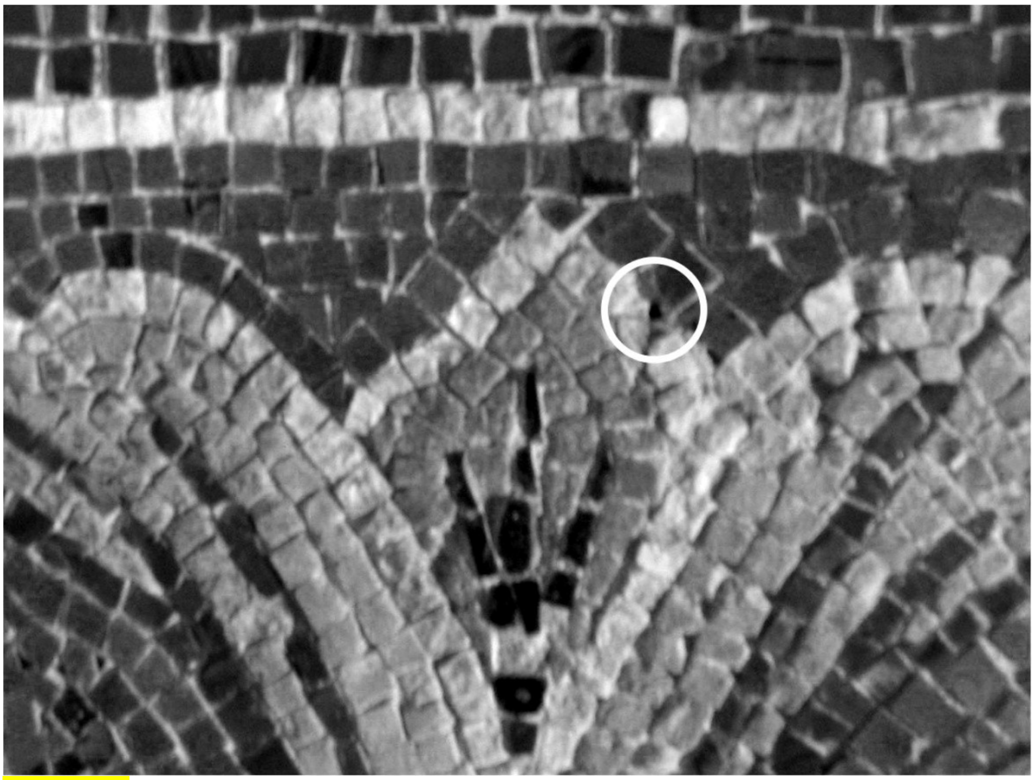


Figure 4. Perforation for the insertion of the current electrode (highlighted by the white circle)

38 different current dipoles were selected for current injection between adjacent electrodes (in horizontal, vertical and diagonal directions) for a total amount 6612 resistance measurements. After noise data rejection, 4919 quadrupolar resistance values were calculated, with the potential dipoles selected as close as possible to the current lines. The inversion model, obtained by means of RES3DINV software, presents an root mean square deviation between observed and calculated resistance values of 17%.

Figure 5 shows the inversion model in depth slices parallel to the acquisition surface. The model presents a superficial conductive anomaly that decreases in lateral extension with depth and that seems to be originated in a close area inside the wall. The walls of the palace are constituted by stones of calcarenite, a sedimentary permeable rock common in Sicilian ancient and modern buildings. Hence it is possible to hypothesize that the variations in the resistivity distribution are due to differences in moisture content in the wall. In figure 6 the deepest slice of the inversion is superimposed to a picture of the fountain hall: it is clear from the image that the lateral position of the conductive anomaly perfectly corresponds to fountain of the hall. Although the fountain is does not collect water from decades, it is possible that there is an accumulation point of water inside the masonry due to a clogged water-pipe of the ancient water collection system of the fountain.

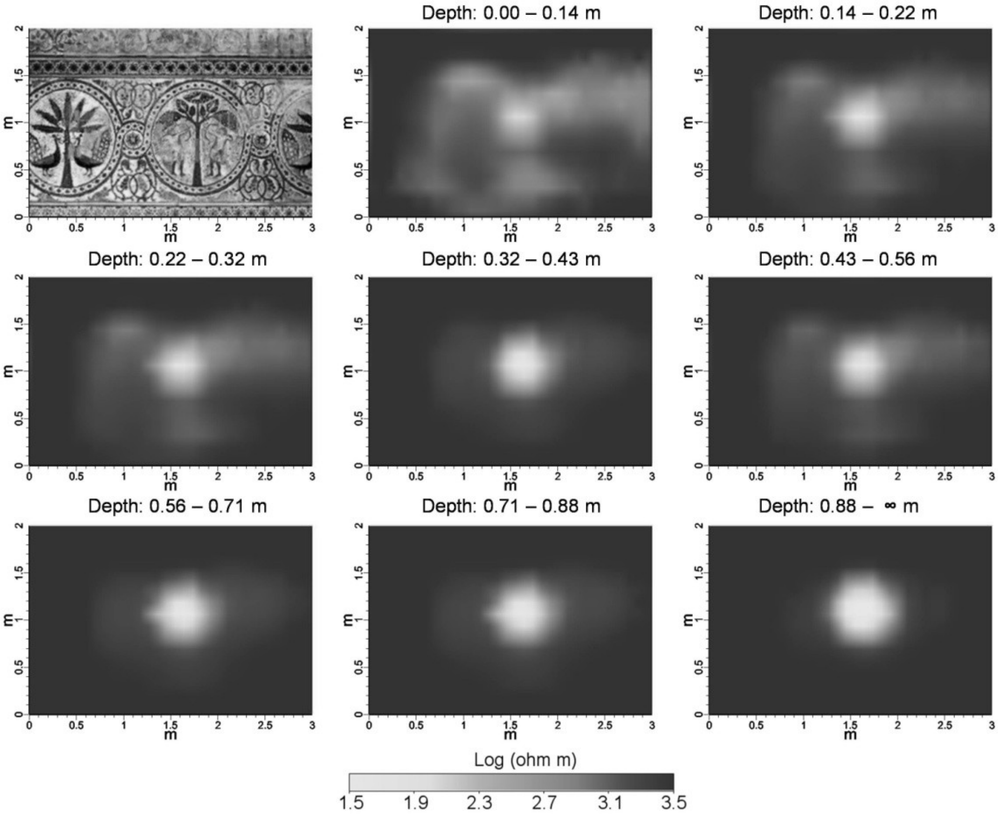


Figure 5. Depth slices of the inversion model.

Figure 6. Superimposition of the deepest slice of the inversion model on the image of the mosaic in the fountain hall.

5. – The ambulatory of the "Villa Romana del Casale" (Piazza Armerina, Italy)

The "Villa Romana del Casale" is an ancient Roman Villa excavated in the archaeological site of Piazza Armerina in 1929. The Villa is famous for its precious floor mosaics, among the largest of Roman times. During the recent restoration of the mosaics, in 2008, a 3D ERT investigation was carried out in the ambulatory of the so-called "Great hunting scene". 704 adhesive ECG electrodes, 60cm spaced, were used for voltage measurements and only 39 small nails (2mm wide) were introduced in small perforations among mosaic tesserae for current injection (figure 7). 108 distinct current dipoles were selected to energize the subsoil. For each current injection three different acquisitions of data were performed, varying the positions of the 256 voltage channels of the MRS256 instrument to measure potentials on all the 704 electrodes of the acquisition grid. The greater distance between the current dipoles and the potential electrodes in comparison with the Zisa field test, together with the lower values of injected current due to greater contact resistances, caused a big noise contamination of acquired data. Only about 22000 resistance values were used for the inversion process. The inversion model presents an root mean square deviation between observed and calculated resistance values of 11%.

In figure 8 a 3D representation of the inversion model is shown. The model presents a deep conductive layer covered by an overburden in which really resistive anomalies are embedded. The deep conductive layer has been interpreted as the saturated zone of the aquifer, also in accordance with a piezometric measurement carried out in a well near the ambulatory. The depth of the contact between the conductive layer and the overburden is not uniform along the ambulatory: probably superficial water and/or a clay lens are present in the first 25m of the model. The more resistive anomalies embedded in the overburden correspond with the concrete basement posed below a portion of the ambulatory floor during the restoration in the 1950s and with some pipelines for water drainage.

Figure 7. Map of the "Villa Romana del Casale" with the location of the ERT investigation. Black dots represent the potential electrodes and black stars the current ones.

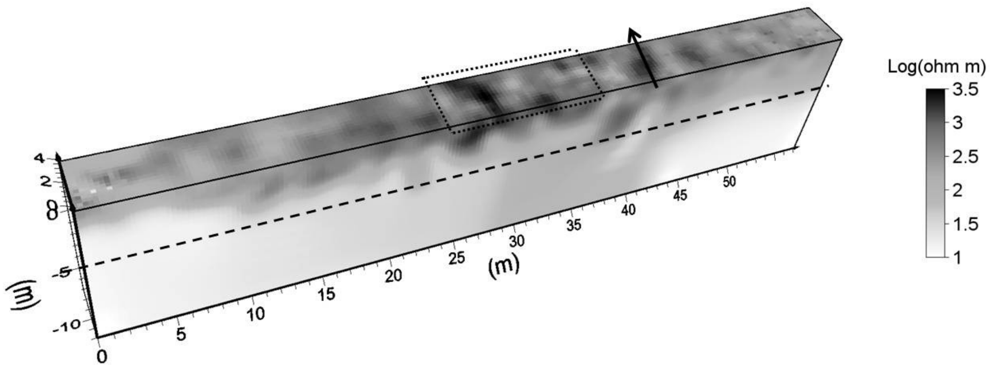


Figure 8. Inversion model of the ambulatory. The dashed line represent the piezometric level; the dotted rectangle corresponds to the concrete basement below the ambulatory floor; the black arrow highlight the location of a pipeline for water drainage.

6. – Conclusions

The MYG methodology presents innovative characteristics in the construction of the quadrupolar sequences of resistance data that allow a significant reduction of both the acquisition time and the invasivity of 3D electrical resistivity tomography. The diminution of the invasivity of ERT investigations consents to apply geoelectrical methods also in the Cultural Heritage field, when the studied media are covered by precious and vulnerable surfaces, like mosaics. The two cases of study presented in this paper demonstrate the capability of electrical resistivity tomography to give great insights in the reconstruction of the structures of buildings walls and foundation soils, being able to recognize the presence of moisture, water table and different construction materials in the analyzed media.

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