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Tumuli exploration using surface 3D Electrical Resistivity Tomography

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Key words: Tumuli, Models, 3D inversion, Archaeological site, Greece.

Introduction

The direct current resistivity method is nowadays a well established geophysical technique, used routinely and successfully in the detection and mapping of concealed subsurface structures, like walls, ditches and anthropogenic or natural cavities (Dahlin and Zhou, 2004). In archaeological geophysics, tombs constitute the most common subterranean manmade cavities of the greatest archaeological and historical importance. Several successful case studies in the detection of tombs have been reported, mainly where the investigated area is almost flat or with relatively small topographic variation. (Nyari and Kanli, 2007).

The detection of tombs inside tumuli constitutes an interesting problem (Tsokas *et al.*, 1995; Vafidis *et al.*, 1995). The tumuli are small artificial hills that cover tombs, usually monumental ones, and perhaps other archaeological structures. Their architectural significance is comparable to the archaeological importance of their content. In fact, tumuli are by themselves monuments of past human activity and offer opportunities to reconstruct important information about the life and customs of the building period.

The non-invasive exploration of tumuli is a challenging geophysical problem. The three-dimensional shape, the abrupt topographical variation and the heterogeneous materials of the tumulus must be taken into special consideration for its successful geophysical investigation (Tsokas and Rocca, 1987). In this work, the surface three dimensional (3D) Electrical Resistivity Tomography (ERT) method was considered, in order to investigate the properties of the tumulus filling material. Different electrode arrays were tested. The method's ability to record buried archaeological structures inside the tumulus, like tombs, is also explored.

The applicability of the 3D ERT method to the reconstruction of tumulus filling material and subsurface structures is approached by numerical modeling and 3D inversion of synthetic apparent resistivity data. The uneven terrain of a tumulus is simulated by a capsized cup topography model having a maximum diameter of 20 m and height of 4 m (Fig. 1b). The filling material of the tumulus consists of two layers with different geoelectrical properties (150 ohm-m and 100 ohm-m respectively) in order to consider the vertical non-homogeneity inside the tumulus due to the different layers of soil, sand and gravels. Furthermore, the horizontal non-homogeneity caused by contact of natural soil and the artificial tumulus material was simulated by assigning the value of 50 ohm-m to the background. The tombs covered by the tumulus were represented by two highly resistive bodies located one at the periphery (dimensions 2x2x1 m)

* *Korea Institute of Geoscience and Mineral Resources (KIGAM), Mineral Resources Research Division, Laboratory of Resource Exploration Development, 92 Gwahang-no, Yuseong-gu, Daejeon, 305-350, S. Korea. (nikos@ims.forth.gr)*
** *Department of Geophysics, School of Geology, Aristotle University of Thessaloniki, 54124, Thessaloniki, Greece.*
*** *Laboratory of Geophysical-Satellite Remote Sensing & Archaeo-environment, IMS-FORTH Rethymnon, Greece.*

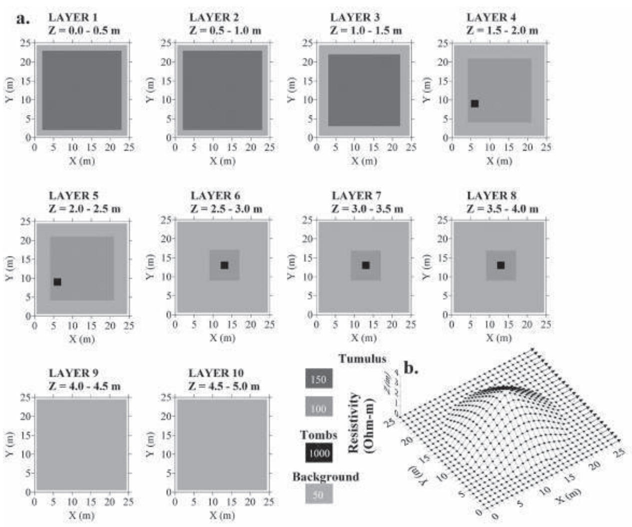

Figure 1 (see color plate): a) 3D resistivity model used to simulate the filling material and the tombs that are concealed inside a tumulus. b) Capsized cup topography model used to simulate the three dimensional shape of a tumulus. The solid lines with the arrows along the X-axis show the direction of each one of the 2D lines used to collect the data. The black dots indicate the surface position (X, Y, Z coordinates) of the electrodes which were placed along each individual 2D line.

and the other below the center (dimensions 2x2x1.5 m) of the tumulus (Fig. 1a).

A surface resistivity survey composed of 26 parallel two dimensional (2D) traverses along the X direction was simulated. The inter-line and the basic unit electrode distances were both set equal to 1 m (Fig. 1b). The resolution capabilities of this specific survey strategy approach those of a complete 3D survey and can maximize the detailed 3D mapping of buried archaeological structures (Papadopoulos *et al.*, 2007). A unique elevation value was assessed for each of the electrodes used to cover the whole area of interest. The Dipole-Dipole (DD), Pole-Dipole (PD), Pole-Pole (PP) and Gradient (GRAD) arrays, which are suitable for multichannel resistivity instruments, were tested. An effort was made to keep similar acquisition parameters for all the arrays for direct comparison of the final inversion models.

Synthetic 3D Modeling and Inversion

A 3D Finite Element algorithm with distorted mesh which was consistent with the tumulus uneven terrain was used to calculate the response of the original model. In order to simulate field conditions, the synthetic potential difference data were contaminated with random electrical noise of 1 mV/A peak-to-peak amplitude (Yi *et al.*, 2001). The 3D resistivity model was described by ten parameter layers of constant thickness equal to 0.5 m. The inversion procedure was based on a smoothness-constrained Gauss-Newton algorithm. The Active Constraint Balancing (ACB) method was also applied in order to enhance the least-squares resolving power and stability (Yi *et al.*, 2001). The effect of tumulus topography was also incorporated in the 3D inversion procedure.

The synthetic modeling approach showed that vertical non-homogeneity due to the different layers inside the tumulus was identified by all the tested arrays with compa-

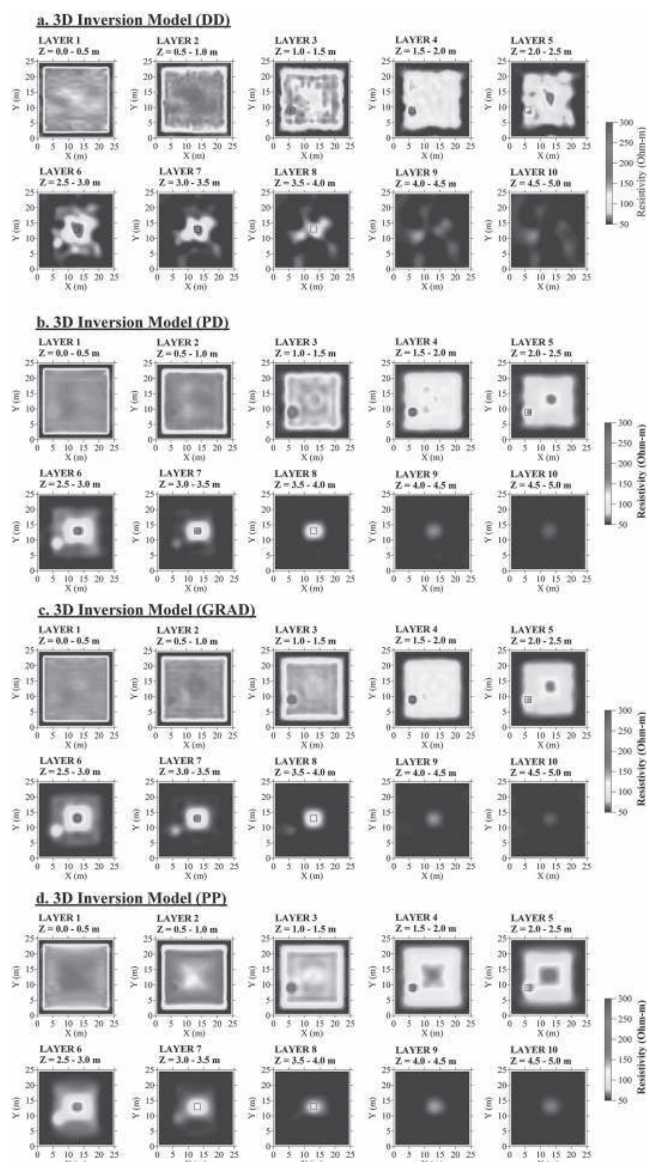

Figure 2 (see color plate): 3D resistivity inversion models for the a) Dipole-Dipole (DD) b) Pole-Dipole (PD) c) Gradient (GRAD) and d) Pole-Pole (PP) arrays.

rable accuracy. The horizontal non-homogeneity between the undisturbed soil and the tumulus artificial material was also reconstructed by all the inversion models (Fig. 2).

Concerning the concealed tombs, the PD array gave a comparatively more resolvable inversion model in relation to the other arrays (Fig. 2b). The horizontal dimensions and the location of the tombs were reconstructed with great accuracy. On the other hand, the top of the tomb located at the periphery was underestimated by the inversion and the central tomb was slightly shifted upwards in the vertical direction. These inversion artifacts can be attributed to the uneven topography and the inability of the Finite Element Mesh to accurately represent the steep topographical variations of the tumulus.

The DD, PD and GRAD arrays seem to have comparable investigation depths. The GRAD model is of comparable accuracy with the PD one indicating that the gradient array can be a strong alternative for a 3D resistivity survey (Fig. 2c). On the other hand the DD array (Fig. 2a) resulted in a more distorted model with less resolution. This is probably caused by the amount of noise, the specific electrode geometry used for the DD and the low signal to noise (S/N) of this specific array. The inherent low resolution of the PP array (Fig. 2d) comprises the main reason of the low resolution of the final inversion model of this array.

Real Data

In order to provide a ground truthing of the above results, a total of thirty eight parallel 2D pole-dipole lines along a single survey direction were measured in order to investigate a small tumulus in the archaeological site of Aegae (Vergina, Macedonia, North Greece). The tumulus covers an area of 22.2x19.2 m and its maximum height is 4 m. The inter-line distance and inter-electrode distance was 0.6 m. The 3D resistivity inversion algorithm managed to reconstruct a model which describes to a certain degree the properties of the tumulus filling material and the basic archaeological structures concealed inside. The high resistivity anomalies A, B, C, D and E are present at different depths and therefore exhibit the highest possibility to indicate buried archaeological features. These results will guide the excavation of the tumulus.

The main aim of this work is to provide an initial insight for collecting and processing 3D surface ERT data for optimum mapping of tumulus properties. In this respect, it is shown that the PD and the GRAD arrays comprise the optimum choices for investigating a tumulus. The dense grid of parallel 2D ERTs collected from a small tumulus in northern Greece contributed to locating high resistivity features which are probably small buried graves.

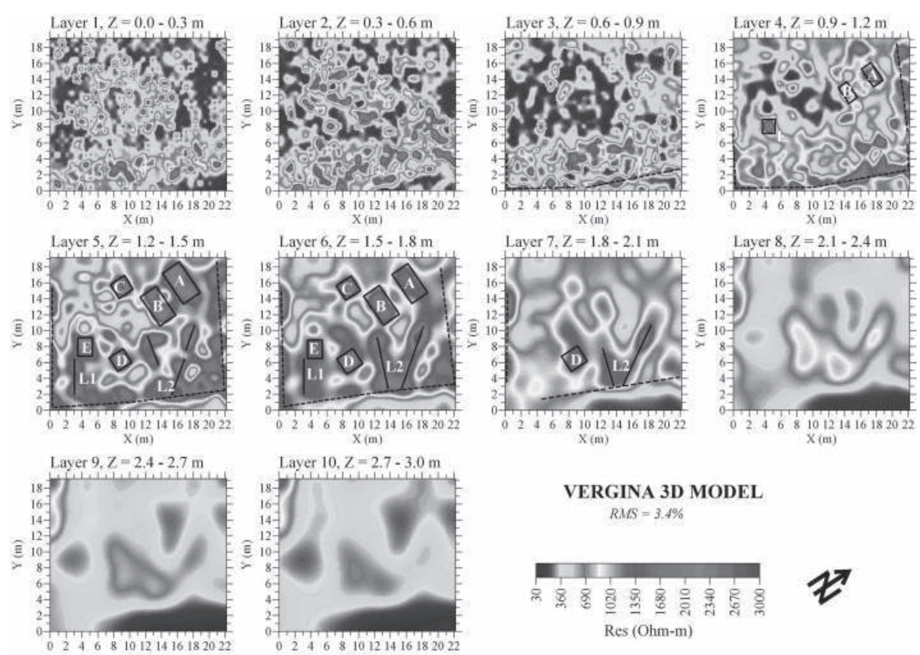

Figure 3 (see color plate): Resistivity inversion model of the Vergina data along with the diagrammatic interpretation of the high resistivity anomalies which are probably caused by archaeological structures buried in the tumulus subsurface.

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