RESISTIVITY MODELLING AND IMAGING METHODS FOR MAPPING NEAR-SURFACE FEATURES: APPLICATION TO A SITE CHARACTERIZATION AT THE ANCIENT TEMPLE OF OLYMPIAN ZEUS IN ATHENS [1]

Ioannis F. Louis1[2], Vasilios C. Karastathis[3], Antonios P. Vafidis[4] and Filippos I. Louis[2]

ABSTRACT

Non-destructive resistivity imaging techniques have been successfully applied at the area of the ancient Temple of Olympian Zeus in Athens aiming to detect subsurface voids responsible for ground failures observed during constructive works in the ground surface. Synthetic modeling and inversion imaging resistivity techniques identified a number of potentially features some of which are attributed to cavities and are more likely to represent relics of an ancient underground conduit system while others are more likely to represent archaeological features such as stone walls or relics of column drums. The geophysical findings were useful for the site characterization and a remedial action plan was recommended to support and improve the ground behavior.

INTRODUCTION

In the context of investigating the engineering geologic conditions at the area of the ancient Temple of Olympian Zeus in Athens, the Geophysics and Geothermics Department, University of Athens conducted in June 2001 an exploration project. This project aimed at providing information for the subsurface structure and to locate evidence for near surface voids.

Most subsurface voids remain undiscovered because they do not reach the ground surface or because unconsolidated surface deposits obscure their entrances. They are usually revealed by chance during quarrying, tunneling or other ground works. Since they usually have very small, near-surface expressions a boring program would not be expected to detect them. Detection of undiscovered voids is very important in characterizing the sites since they can produce ground failures that have an adverse effect on nearby structures.

There are a variety of geophysical techniques that can be used to detect the presence of voids below the subsurface. All of them are based in that there is an obvious physical contrast between a void and the surrounding rock. The last decade with the advent of fast computing technologies the electrical resistivity tomography has become a widely used tool for this purpose (Noel & Xu, 1992; Loke and Barker 1994; Dahlin 1996; LaBrecque et al. 1996; Oldenburg and Li, 1999).

THE SITE

Within the frameworks of the Cultural Olympiad 2001-2004 and under the auspices of the Hellenic Ministry of Culture the ancient Temple of Olympian Zeus in Athens was selected for the presentation of the choral symphony *"Mythodea"* as a prelude to the 2004

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[2] Geophysics – Geothermics Division, Geology Department, University of Athens, Athens 15784, Greece. jlouis@geol.uoa.gr, flouis@geol.uoa.gr

[3] National Observatory of Athens, Institute of Geodynamics, Athens 11810, Greece. karastathis@gein.noa.gr

[4] Applied Geophysics Laboratory, Department of Mineral Resources Engineering, Technical University of Crete, Chania, Greece. Vafidis@mred.tuc.gr

Olympics. The temple of Olympian Zeus in Athens (Olympieion) is one of the largest in the ancient world; it was 362 feet long and 143.3 feet wide. There were two rows of 20 columns on the sides and three rows of eight columns on the end. Only 16 are now preserved (Fig. 1). The stage of the *"mythodea"* concert was built in front of the standing temple columns.

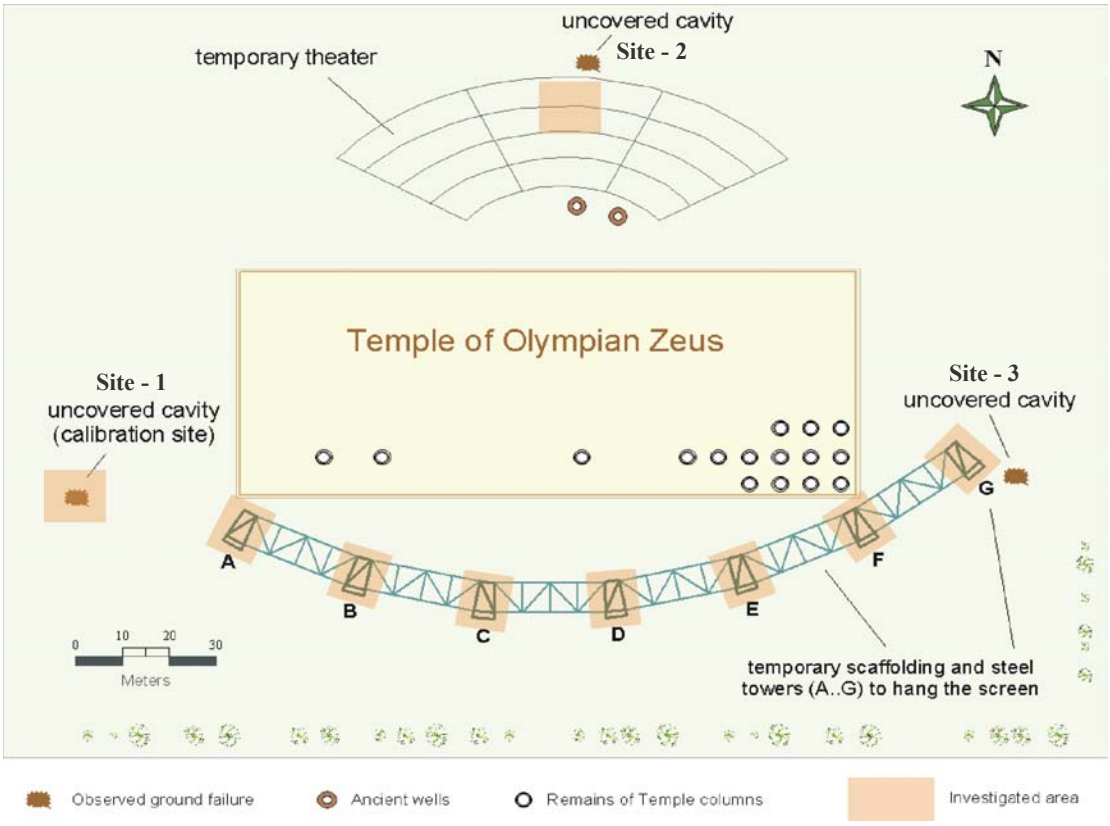


Fig. 1. Location map of the investigated area.

The week preceded the presentation trucks and cranes transported equipment onto the old temple area to set up a temporary amphitheatre (Fig. 2), scaffolding and a construction of six steel towers (Fig. 3) to support a more than 150 meters wide and 20 meters high white screen (Figure 4) to project images during the concert.



Fig. 2. The temporary amphitheatre and the Temple of Olympian Zeus in background. (www.vangelis.myweb.nl/mythodeagallery.htm)



Fig. 3. Scaffolding and steel towers to support the large screen for images projection. (www.vangelis.myweb.nl/mythodeagallery.htm)

During construction a vehicle uncovered the opening of three small cavities (Fig. 1) near the temple. The risk of the existence of similar subsurface cavities at the placement sites of the heavy towers and the expressed concern of the archaeologists that due to a possible ground failure the winds would knock over the towers and cause damage to the ancient monument leaded the Ministry of Culture to assign an engineering site characterization study aiming at providing locations of possible ground failures and taking strict measures for their remediation.



Fig. 4. Snapshot from the choral symphony presentation. In background the white screen hanged on the steel towers (www.vangelis.myweb.nl/mythodeagallery.htm).

Engineering site assessment usually includes determining the geologic character of the subsurface when a ground failure has occurred and provides the information needed to determine the extent and scope of a specific problem and to design remediation strategies. This is based primarily on a series of closed spaced boreholes to insure that important features are found. Since the area of the old temple is a preserved archaeological site and no boreholes or excavations could be carried out without a time-consuming bureaucracy a quick geophysical survey was conducted (Louis 2001) just two days earlier the presentation aiming to provide the information needed for the site characterization.

GEOLOGY OF THE AREA

Bedrock consists of the Athens "schists", much of which is covered by Quaternary layers of varying thickness. The Athens schists actually include sandstones, slates, marls, phyllites, cherts and masses of brecciated or crystalline limestone. The upper units of the Athens "schists" include marls, platy limestones, sandstones, conglomerates, and breccias.

THE METHOD

A non-destructive high-resolution resistivity tomography survey was carried out with the primary objective to locate evidence for near surface cavities responsible for possible ground failures at the placement sites of the heavy towers. Other subsurface objects such as archaeological remains were also of concern if they exist on the site.

In electrical resistivity tomography applications current is introduced into the ground through one pair of electrodes. A second pair of electrodes is then used to quantitatively measure the voltage pattern on the surface resulting from the current flow pattern of the first set of electrodes. If multiple electrodes are used and the results recorded automatically the

area to be examined can be searched more efficiently, and also probed at various depths at the same time. A fast numerical approach is then used to optimize an initial multiplayer model constructed usually directly from the observed apparent resitivity values. A finite difference or finite element technique is usually used to calculate the 2-D forward response of the model. By subsequent iterations the model is upgraded until a minimum (or an acceptable) rms misfit between the observed and model pseudosection is achieved.

SYNTHETIC MODELING

Prior to field-data acquisition a geophysical survey of the same cross-section was simulated to choose the acquisition parameters for optimum detect ability and resolution. This effort had two goals; the first was to test the capability of the method to reconstruct images of voids and archaeological features expected to be present in the subsurface. The second benefit was to use the information obtained from the synthetic-data inversions as constrains helping the interpretation of the field-data inversions. Resistivity data were processed at the Applied Geophysics Laboratory, Department of Mineral Resources Engineering, Technical University of Crete, using the commercial software packages RES2DINV and RES2DMOD. A two dimensional finite element algorithm was used to calculate the direct current response (apparent resistivities) from a set of resistivity models intended to reflect real geological or environmental situations for the local area.

The first group of the synthetic models was constructed on the basis of the spatial extent of the already known void as it was measured directly from the field. A resistivity value of 17000 ohm-m was used to represent the air filled cavity structure buried at the depths of 0.2 and 1 meter. The second group included the case of a stone block structure. The resistivity value of 5000 ohm-m was used to represent the marble structure buried at the depths of 0.2 and 1 meter. In both models a resistivity value of 250 ohm-m was chosen to represent the background material (marls, sandstones and conglomerates) whose presence is verified in the broader area from previous geological observations.

The imaging abilities of the electrode arrays were examined using the least square inversion technique and three data densities corresponding to three different electrode spacing (0.2, 0.3 and 0.6 meters). Gaussian noise was also added to both background and target models to demonstrate that the inversion scheme is reasonably robust and will work in an environment with unsystematic geologic or instrumental noise. RES2DINV software used for the inversions is based on the smoothness – constrain least squares method and basically tries to reduce the difference between the calculated and measured apparent resistivity values with respect to some smoothness constraints such as the complexity of a model.

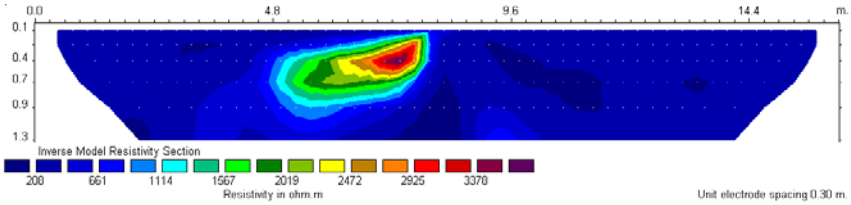
The resulting inversions were compared with the original input models for the three types of electrode separations and depths of burial. In general they gave relatively high resolutions inside the images for the shallow target models. The deep structure models revealed that although the geometries of the resistivity anomalies were sufficiently reconstructed however the absolute resistivity values inside these structures were not recovered in an efficient way. That useful conclusion was going to be used for interpretation purposes as well since same resistivity structures at greater depths showed great divergence in the inversion results. In general the resistivity values inside the anomalies at the final tomograms were smaller than the actual ones and especially with increasing depth, while the background values were recovered well enough. The above phenomenon was observed in all types of electrode spacing indicating in that way the already known loss of resolution with increasing depth of investigation.

Since the two higher density data packages (0.2 and 0.3m electrode spacing) gave no major differences on the inversion results the 0.3m spacing was chosen for the whole survey

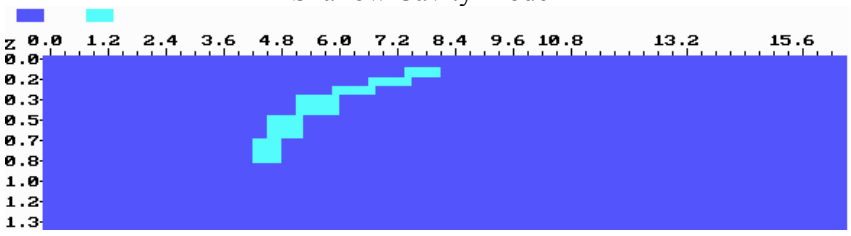
since it required half the acquisition time and no significant loss in resolution for the desired target. The fairly accurate inverted images and the positions of the initial known models in relation to the sections are depicted on Figures 5 and 6.

CAVITY SYNTHETIC MODELING

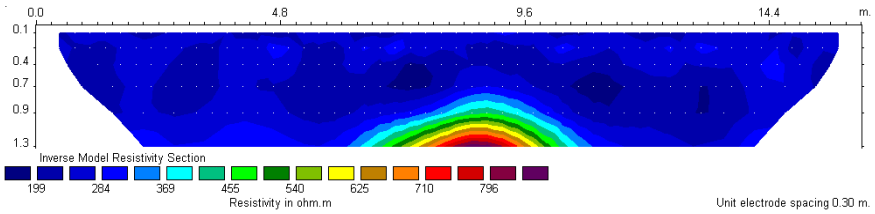
Shallow Cavity Inverted Image



Shallow Cavity Model



Deep Cavity Inverted Image



Deep Cavity Model

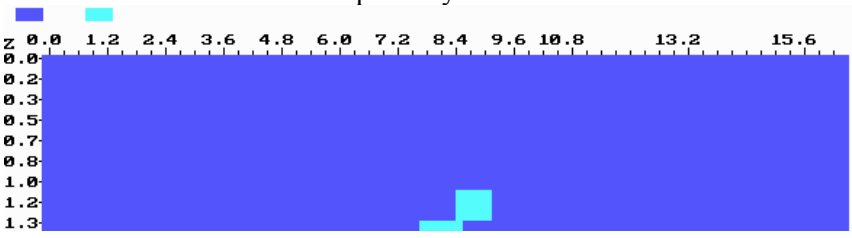
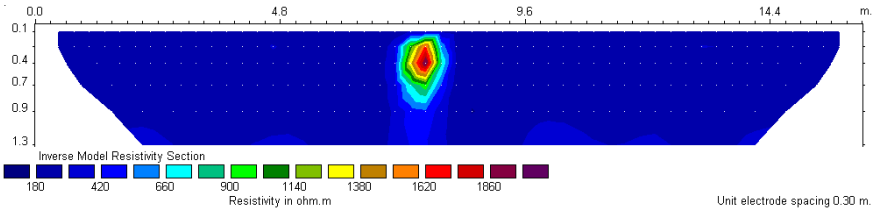


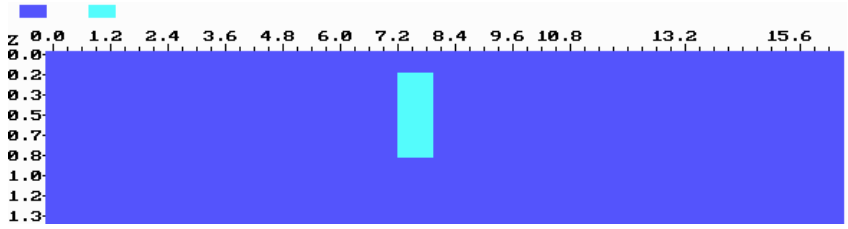
Fig. 5. Synthetic modeling results for the cavity model.

STONE BLOCK SYNTHETIC MODELING

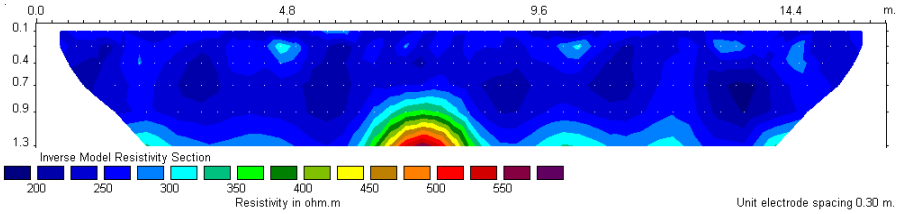
Shallow Stone Block Inverted Image



Shallow Stone Block Model



Deep Stone Block Inverted Image



Deep Stone Block Model

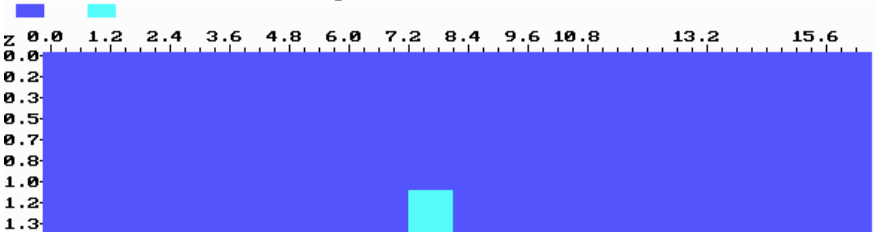


Fig. 6. Synthetic modeling results for the stone model.

These numerical comparisons also showed that data with intermediate random noise levels could give at very contrast environments high-resolution images depending always on both the data density and the depth of the prospect.

By summarizing, the synthetic modeling indicated that 0.2m is the optimal electrode spacing to delineate the specific targets. However the efficient spacing of 0.3m was chosen to speedup the fieldwork with no significant loss in resolution. While the background resistivity values were recovered well enough, the recovered target values were lower than the actual ones and especially with increasing the model depth. Thus, the inverted image of a near-surface cavity with the chosen geometry is expected to exhibit a resistivity variation 3000-4500 ohm-m. Similarly, the response of a stone block will be exhibited with a resistivity variation 1600-1900 ohm-m. At greater target depths the expected resistivity variations are reduced to 700-800 and 500-600 ohm-m respectively. If cavity targets are filled or partially filled their response is expected to overlap with that of stone features making in that way the target discrimination difficult.

To test the synthetic modeling outcomes in practice the chosen geometry of electrodes was first applied over the revealed cavity at Site-1 (Fig. 1). Two 2D resistivity profiles Line-A and Line-B (Fig. 7) were conducted, parallel and perpendicular at the subsurface direction of the revealed cavity, by using the Wenner configuration of electrodes. Both 2D profiles were sufficiently spread to provide 12m of complete data coverage for the desired depth of investigation.

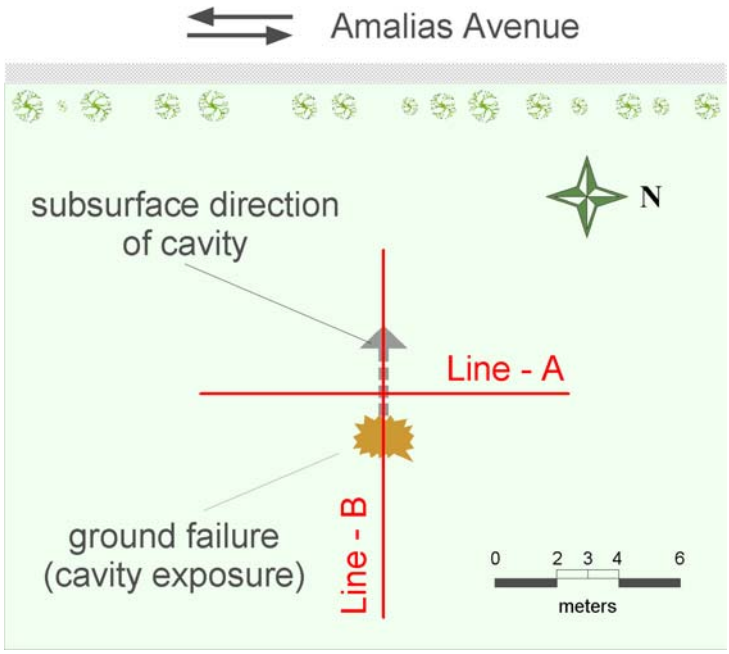


Fig. 7. Detailed location map of Site-1.

The inverted images A and B (Fig. 8) delineate the known cavity case fairly accurate. Both inclination and extent of the linear lineament of image B are fairly identified with the measured characteristics of the revealed cavity (Fig. 9).

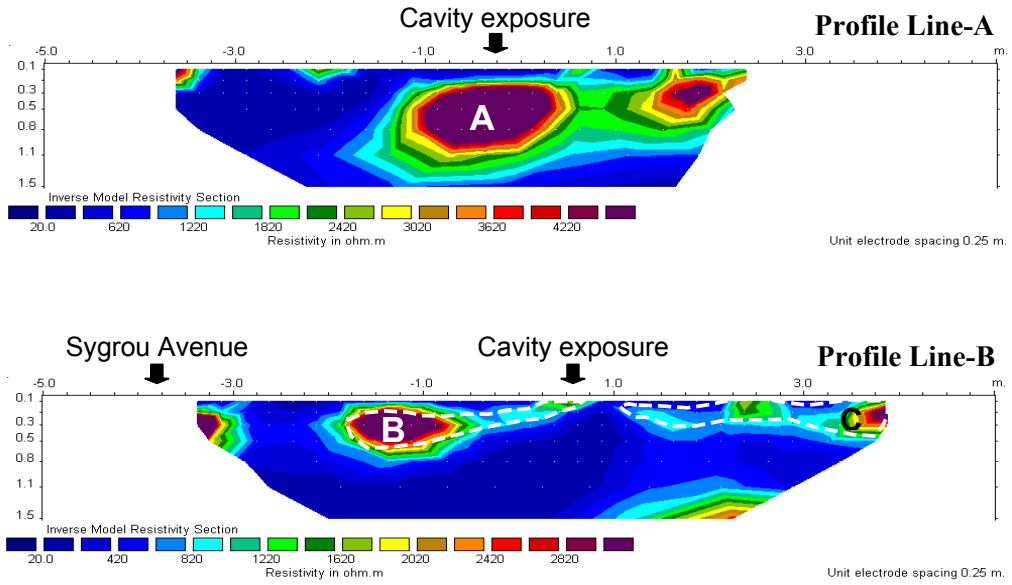


Fig. 8. 2D resistivity images of profiles Line-A and Line-B.

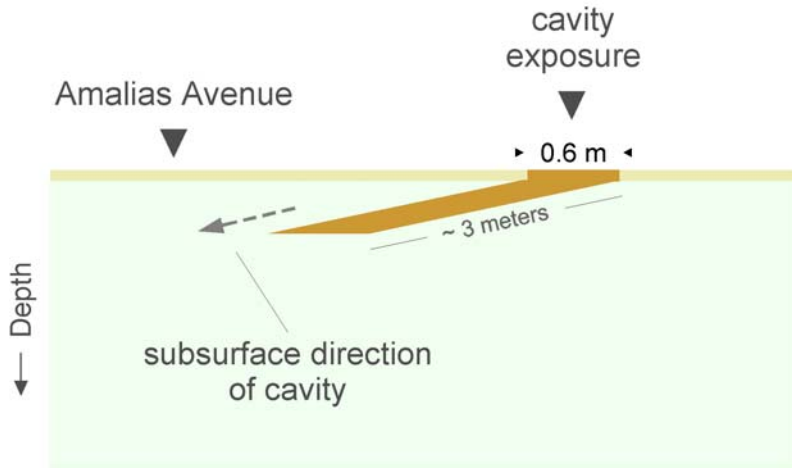


Fig. 9. Sketch diagram of the revealed cavity characteristics as they were measured in the field.

Further, a pronounced resistive feature, C, is now seen to be situated at the right hand side of profile Line-B. Judging by the accuracy of the reconstruction of the known revealed cavity, all reasons are satisfied to interpret the high resistive block C as an indication of unknown cavity.

DATA ACQUISITION – PROCESSING

In field-data acquisition four lines namely, LINE-1, LINE-2, LINE-3 and LINE-4 (Fig. 10) were scanned in each one of the three placement sites C, D and F using the electrical tomography method and the Wenner-Schlumberger array with a maximum N separation (ratio of maximum and minimum electrode spacing) equal to 12. In placement site E an extra line

namely LINE-5 was added (Fig. 10) between lines LINE-1 and LINE-2. Data were collected with the SYSCAL R1 Plus resistivity meter (IRIS).

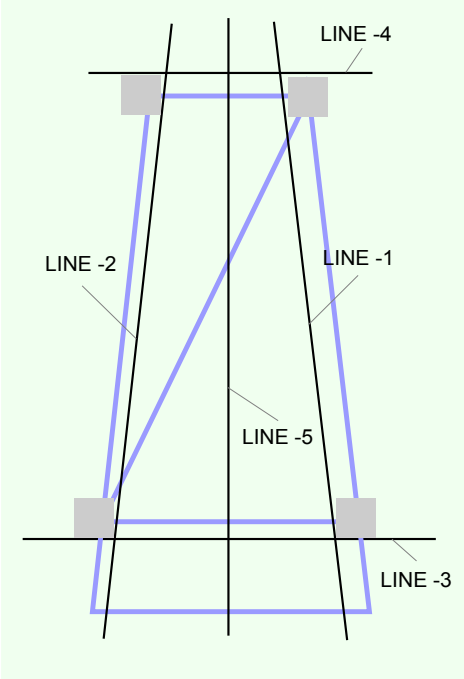


Fig. 10. Profile lines acquisition pattern.

The apparent resistivity pseudosection produces a distorted image of the subsurface resistivity. Inversion of the field observations is the standard procedure to obtain an estimate of the true resistivity. The true resistivity structure was interpreted using 2.5D smoothness constrained inversion to invert the apparent resistivity data (Tsourlos, 1995; Tsourlos et al., 1998) by employing a quasi-Newton technique to reduce the numerical calculations (Loke and Barker 1994). The algorithm is iterative and fully automated. The inversion estimates a resistivity model by minimizing the difference between the observed and the calculated data. The smoothness constrained inversion method imposes another condition, namely that the roughness of the resistivity model is minimum.

RESULTS – INTERPRETATION

The inverted resistivity sections, fasten into a pseudo 3D configuration according to their layout pattern (Fig. 10), are depicted on Figures 11, 12, 13 and 14. As it can be observed from the data the investigated area is geophysical complex with variable range of resistivity values recorded across the sites. The 2D resistivity tomograms show a large number of anomalies characterizing the response over the sites, which may reflect underlying natural and or man-made features.

A total of 17 high to very high resistance anomalies within the investigated sites were identified and numbered. By observing the resistivity tomograms it is obvious that most of the anomalies, divided in groups, constitute slices of greater rectilinear structures. Such groups are [3, 5, 6] and [1, 2] in tower C (Fig. 11), [12, 8, 9, 10] and [11, 13] in tower D (Fig. 12), [14, 15, 18] and [16, 19, 18] in tower F (Fig. 14).

However, without constrains, there has to be a measure of uncertainty in the interpretation and the decision to recommend remedial actions, as it is difficult to reliably separate responses caused by natural or man-made cavities from some types of archaeological features which may be found in the environment of the old temple.

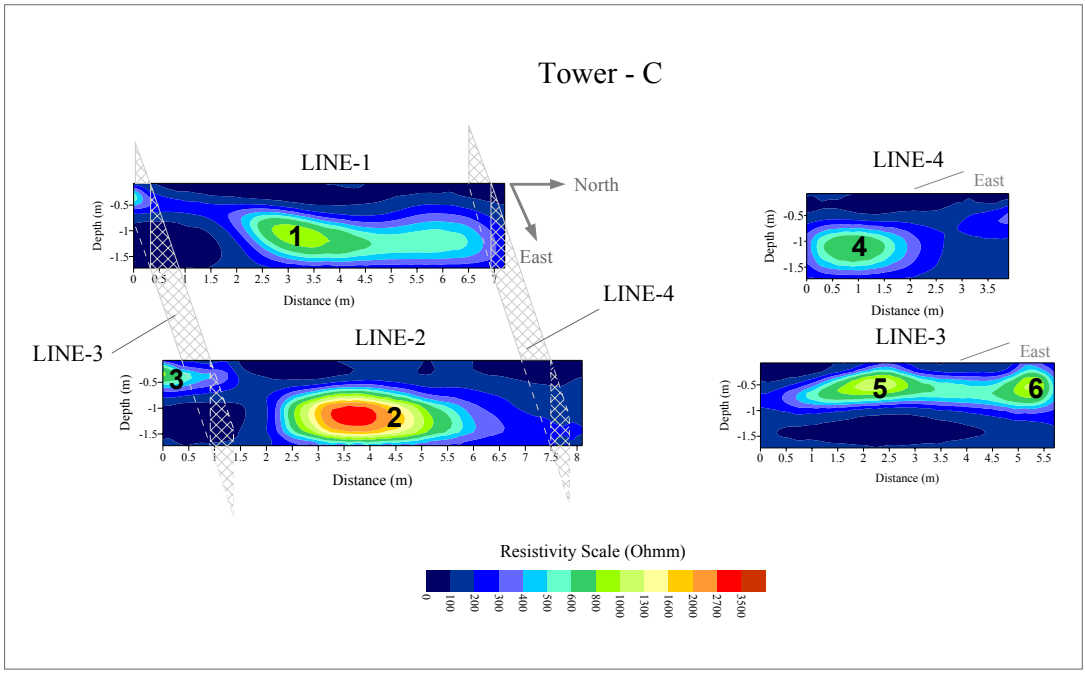


Fig. 11. 2D resistivity tomograms in the placement area of tower C.

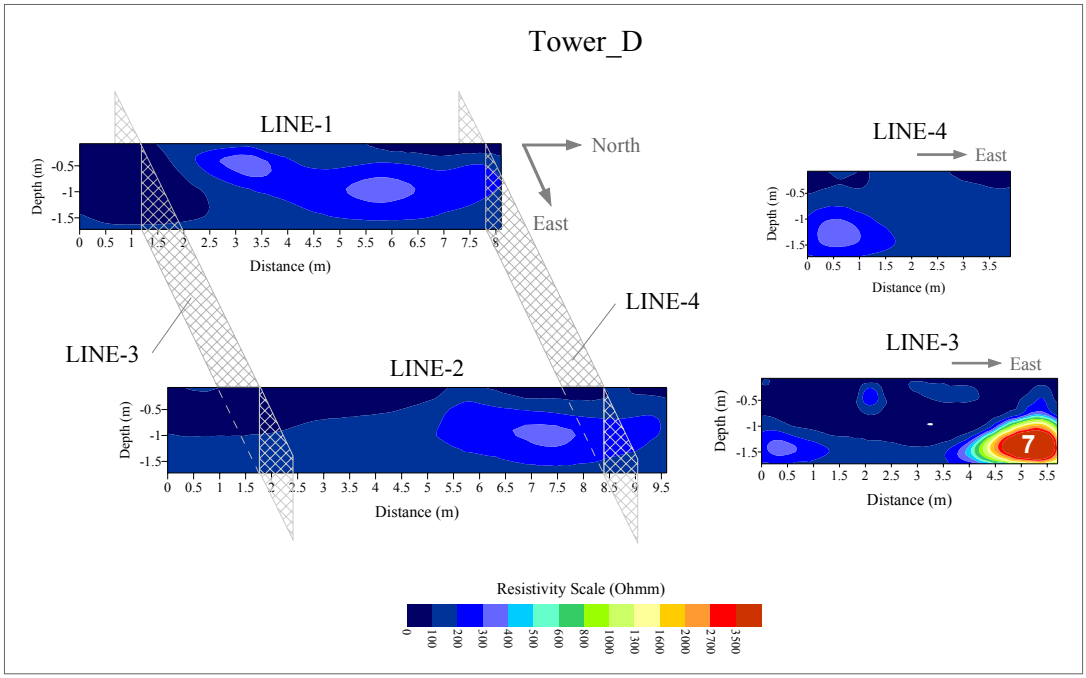


Fig. 12. 2D resistivity tomograms in the placement area of tower D.

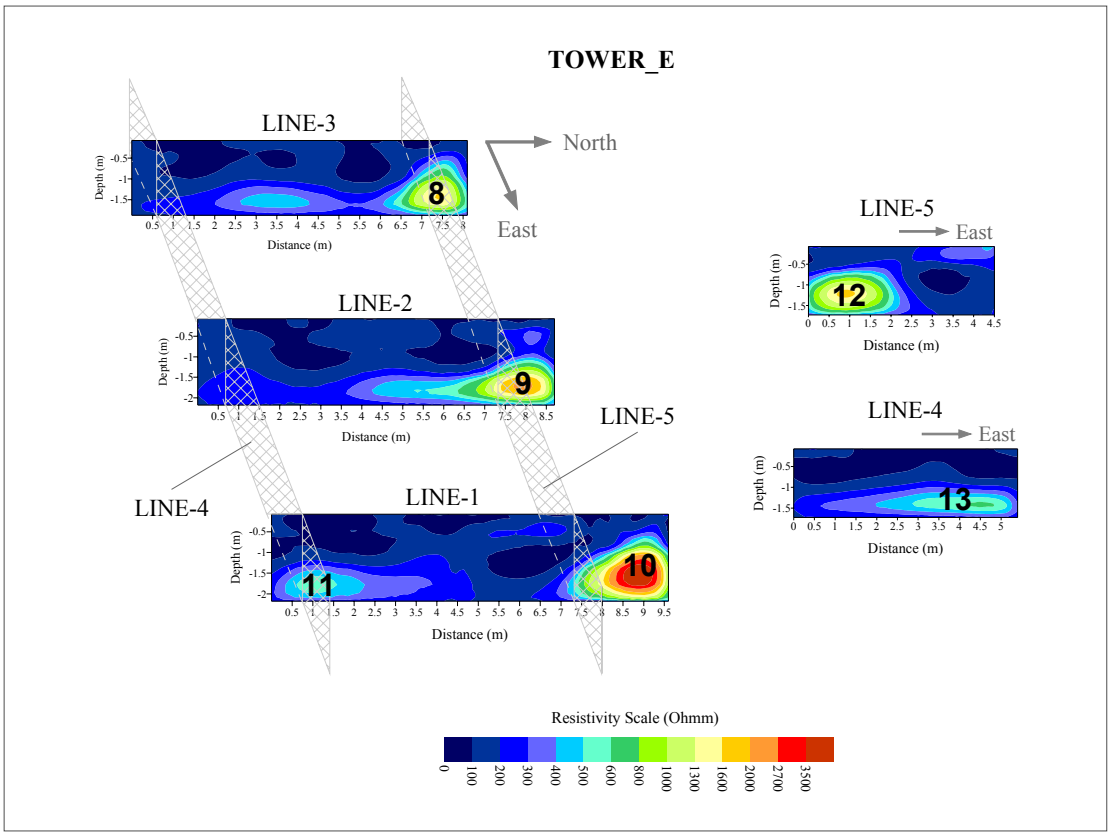


Fig. 13. 2D resistivity tomograms in the placement area of tower E.

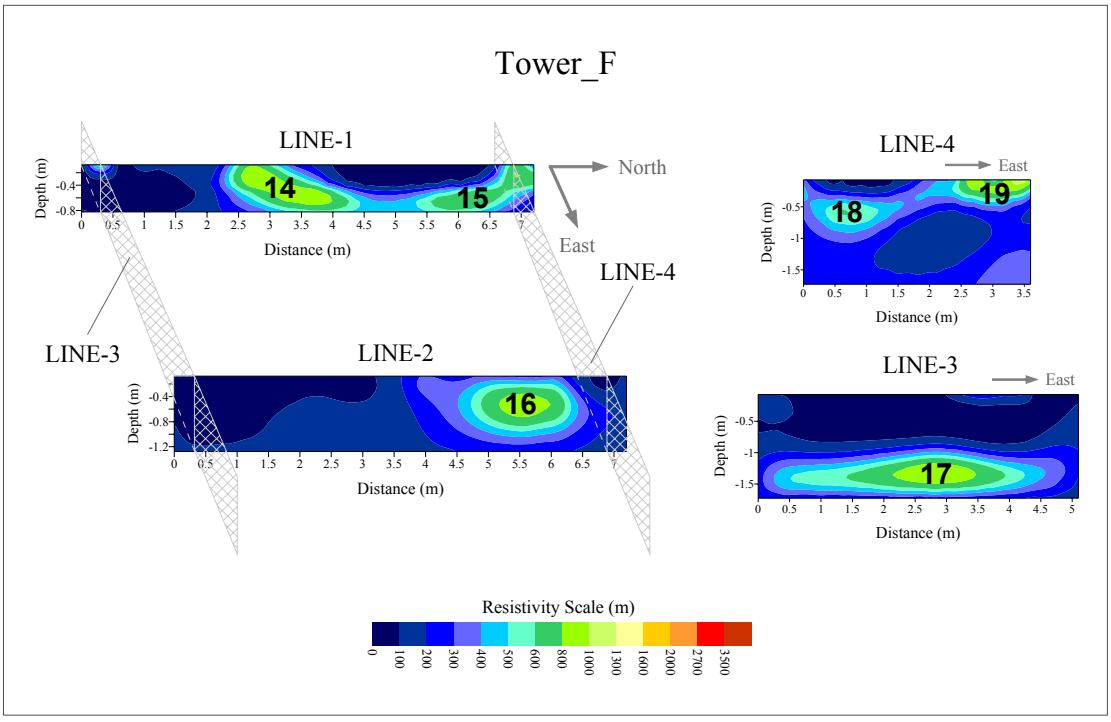


Fig. 14. 2D resistivity tomograms in the placement area of tower F.

The synthetic modeling data and the calibration results over the Site 1 (Fig. 1) helped to discriminate between different subsurface features including empty or partially filled cavities and archaeological remains. Empty shallow cavities are distinguishable as very high resistivity structures (> 3000 ohm-m) in the resistivity tomograms. Shallow stone remains are distinguishable as moderately high resistivity structures (1500-1900 ohm-m). These anomalies helped to define both the size and depth of the structures. The interpreted rectilinear resistant features, distinguished as cavities or archaeological remains, at each tower site are depicted on Figure 15.

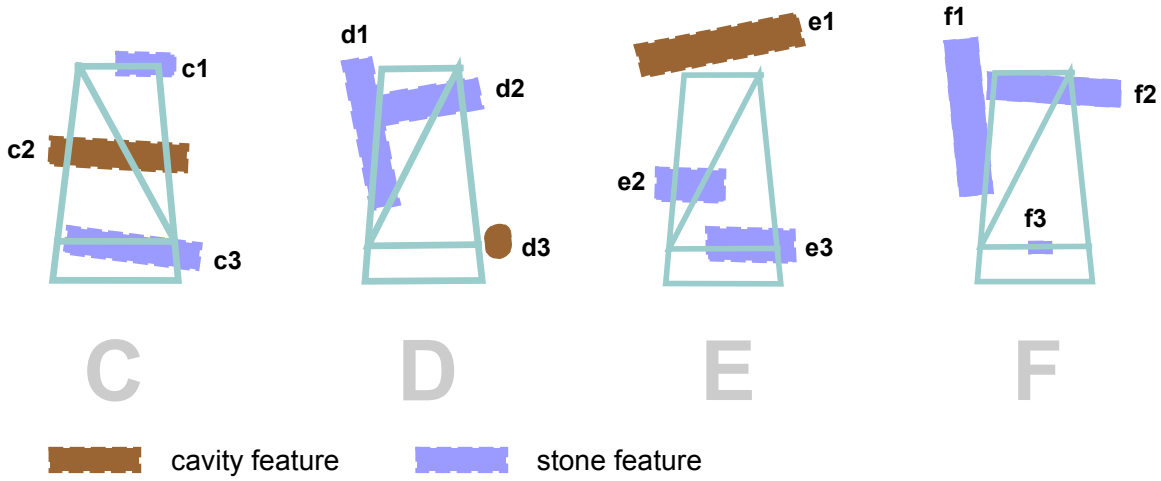


Fig. 15. Interpreted features.

Thus, across tower C (Fig. 15), the rectilinear feature (**c2**) with orientation E-W and dimensions 1m in diameter and 4m in length, detected at 1m depths, is attributed to a cavity. The rectilinear features (**c1**) and (**c3**) with dimensions 0.6m in diameter and respective lengths and depths 1.5m, 1m and 4.5m, 0.3m are attributed to stone features of archaeological interest. Similar interpretations were made for tower sites D, E and F where the rectilinear features (**d3**) and (**e1**) (Fig. 15) with orientations E-W and NE-SW and dimensions 1m in diameter and 1m, 4.5m in length detected at 1m depths are attributed to cavities. Features (**d1**), (**d2**), (**e2**), (**e3**), (**f1**), (**f2**) and (**f3**) (Fig. 15) are attributed to stone remains.

According to archaeologists (personal communications) it is possible that these rectilinear features, attributed to cavities, are more likely to represent relics of an ancient drainage system. The presence of a major drain or water conduit passing through the grounds of the Temple fits with a reference of Pausanias who claims, "*A chasm several feet across in the ground on the site is where the floodwaters drained away*". (www.lilt.ilstu.edu/drjclassics/sites/athens/OlympianZeus/lecture.htm)

The eastward orientation of these rectilinear features is also another indication that they might used to discharge waters towards to the bank of the ancient river Heridanus whose trace passes close to the eastern boundary of the temple. Since, due to the very limited time available in the field, the geophysical survey could not be expanded further beyond the strict area of the towers sites the full extend of this drainage system is unclear.

CONCLUSIONS

The sparse distribution of the investigated sites has made reliable interpretation of the geophysical response difficult over much of the temple area. Nevertheless a number of

potentially features have been identified. Sites C, E and F contain several high to very high resistance anomalies which are strongly suggestive of artificial features. Some of these are attributed to cavities which produce very high resistance anomalies and are more likely to represent relics of an ancient underground conduit system while others (although difficult to interpret precisely) are more likely to represent archaeological features such as stone walls or relics of column drums. Unfortunately the results are insufficiently clear to enable detailed reconstruction, but a detailed investigation would undoubtedly result in the recovery of a more complete ground plan of the greater area of the ancient temple.

The high resistance anomalies only appear well defined where they cross through areas of lower background resistance. This seems to suggest that the lower resistance areas have been disturbed or cut by the construction of the features that have caused the high resistance anomalies as would be the case of the stone features or the remains of a conduit system (cavities) which are responsible for the observed ground failures during the preparative works preceding the choral symphony presentation.

From the site characterization point of view the geophysical survey results were positive. Three sites with strong indications of underground existing cavities were cleared but no boreholes or excavations could be carried to verify the findings without the outflanking of a time-consuming bureaucracy. Thereby the sites were characterized as a priori vulnerable areas and a remedial action plan was recommended to support the steel towers by sinews and reinforce their concrete pedestals.

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