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Resistivity modelling and imaging methods for mapping near-surface features: Application to a site characterization at the ancient Temple of Olympian Zeus in Athens

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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 modelling and inversion based 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 behaviour.*

Key Words: *Resistivity Imaging, Site Characterization, Archaeometry*

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 an exploration project in June 2001. 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 unconsolidated surface deposits obscure their entrances. They are usually exposed by chance during quarrying, tunnelling or other ground works. Since they usually have very small, near-surface features a drilling 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 on the assumption that there is a sharp physical contrast between a void and the surrounding rock. The advent of fast computing technologies permitted a broad use of the electrical resistivity tomography for this purpose (Noel and 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 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.

The week preceded the presentation trucks and cranes transported equipment onto the old temple area to set up a temporary amphitheatre (Fig. 2), and to construct six temporary steel towers (Fig. 3) to support a huge white screen (Fig. 4) for projecting images during the concert.

A vehicle uncovered the opening of three small cavities (Fig. 1) near the temple during the construction. 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 pos-

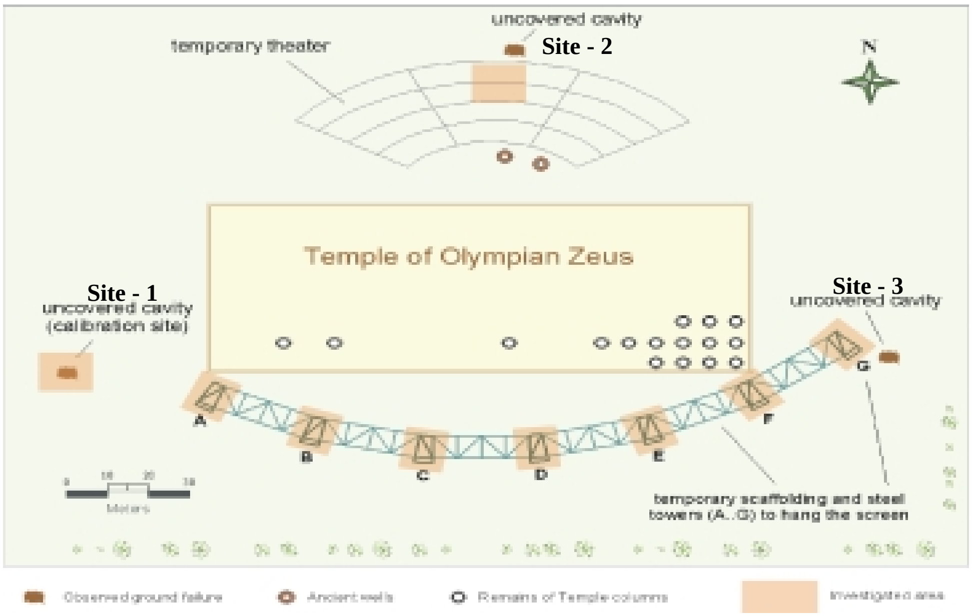


FIG. 1. Location map of the investigated area.

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).

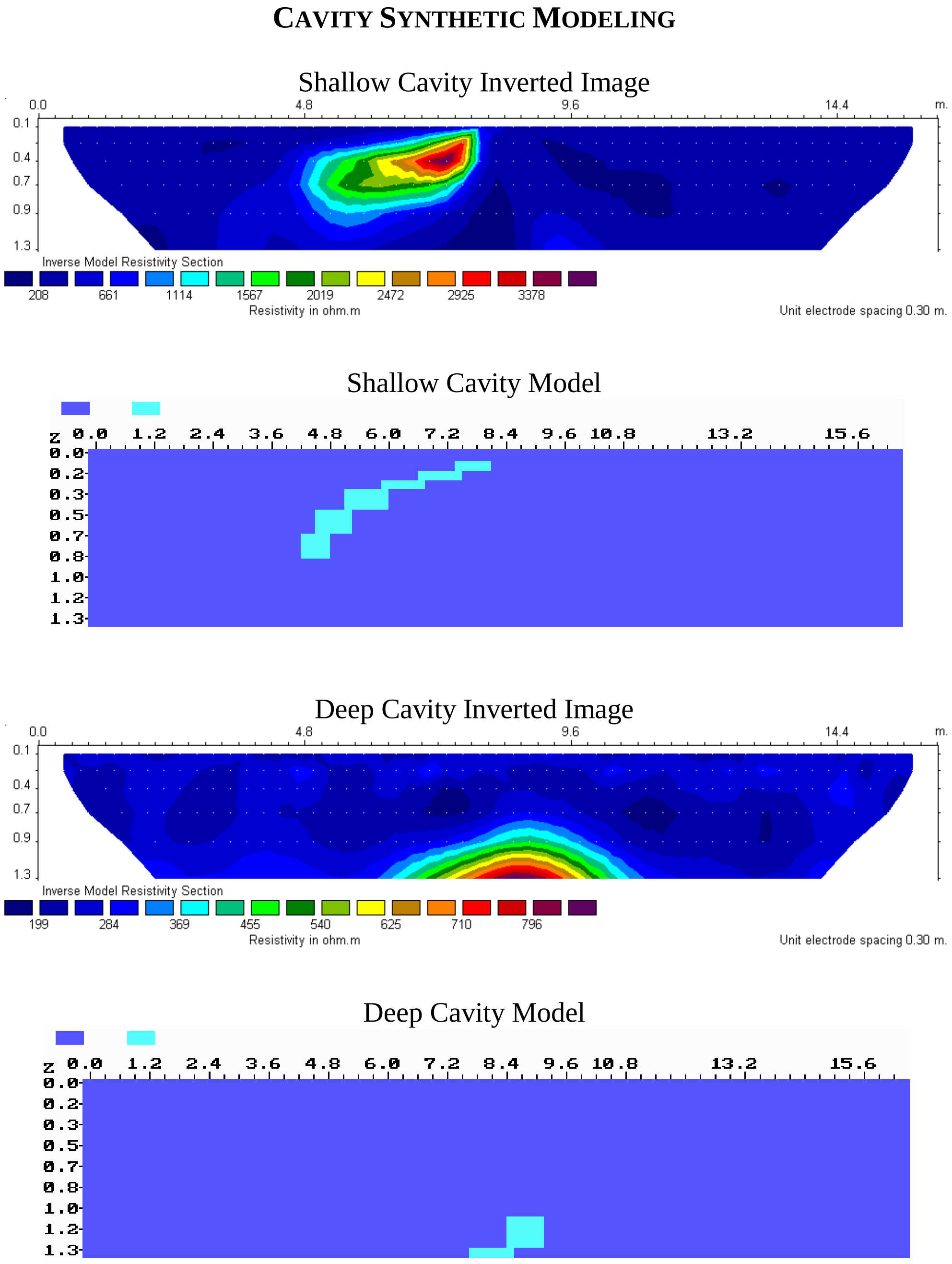
FIG. 4. Snapshot from the choral symphony presentation. In background the white screen hanged on the steel towers (www.vangelis.myweb.nl/mythodeagallery.htm).

sible ground failures and taking strict measures for their remediation.

Engineering site assessment usually includes determining the geologic character of the subsurface when a ground failure has occurred and provides the required information 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 detected. 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 and Papadopoulos 2001) just two days earlier the presentation aiming to provide the information needed for the site characterization.

GEOLOGICAL UNITS IN THE SURVEY AREA

The 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.


CAVITY SYNTHETIC MODELING

Shallow Cavity Inverted Image

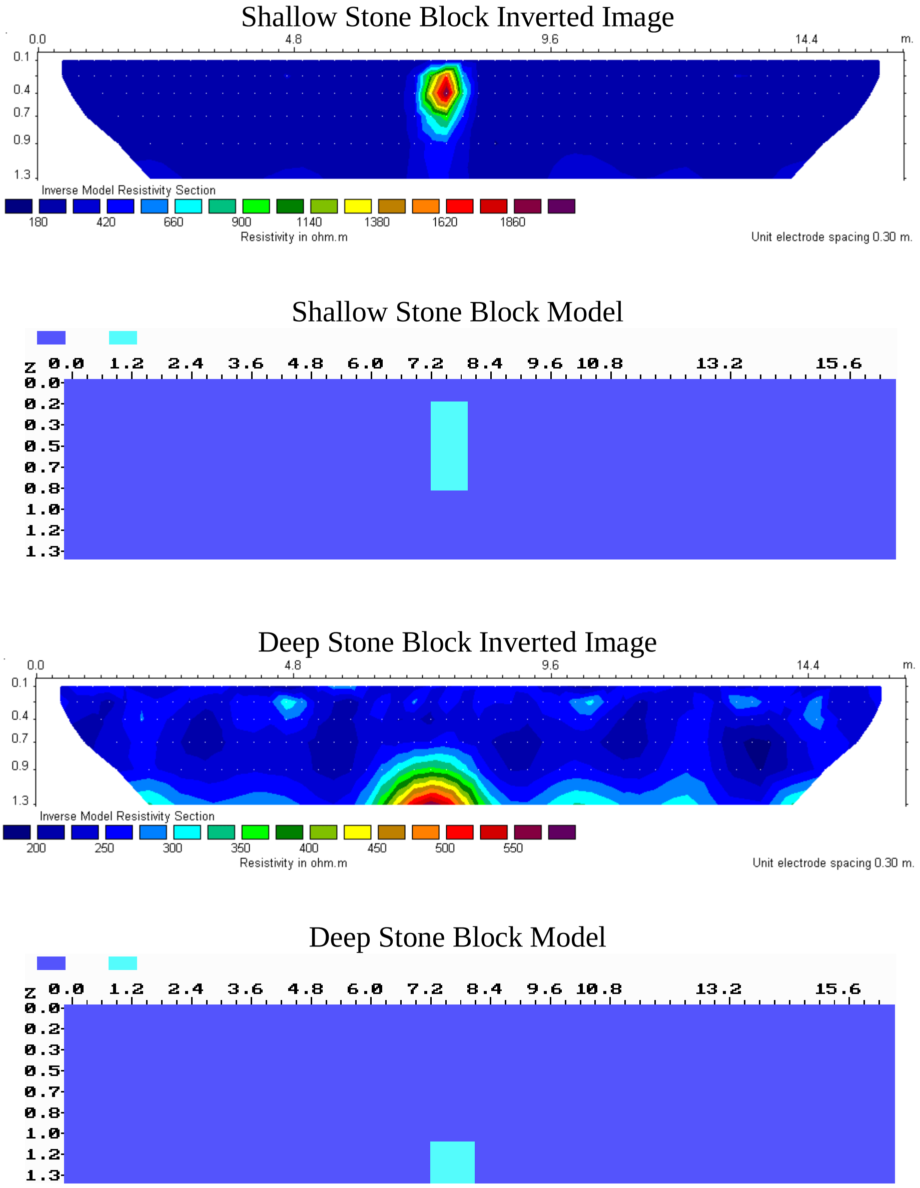
Shallow Cavity Model

Deep Cavity Inverted Image

Deep Cavity Model

FIG. 5. Synthetic modelling 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 modelling results for the stone model.

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

SYNTHETIC MODELLING

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. The resistivity data were processed at the Applied Geophysics Laboratory, Department of Mineral Resources Engineering, Technical University of Crete, using the commercial software package RES2DMOD. A two-dimensional finite element algorithm was used to calculate the direct current response (apparent resistivity) from a set of resistivity models intended to reflect real geological or environmental situations for the local area.

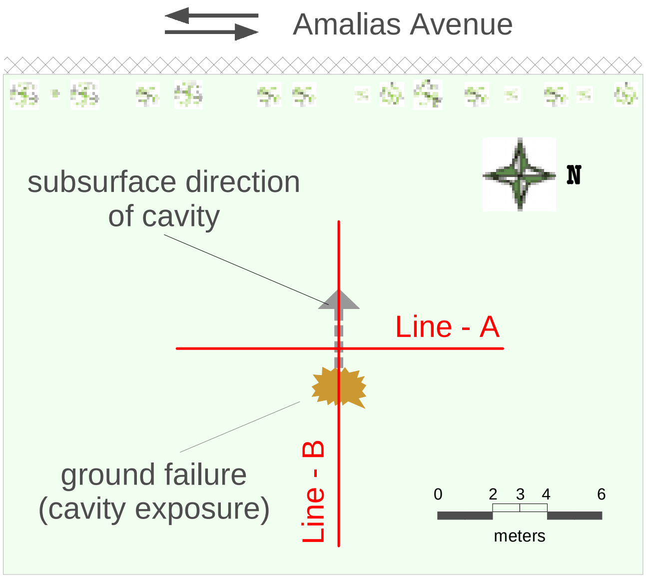


FIG. 7. Detailed location map of Site-1.

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.

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 exposed that although the geometries of the resistivity anomalies were sufficiently reconstructed however the

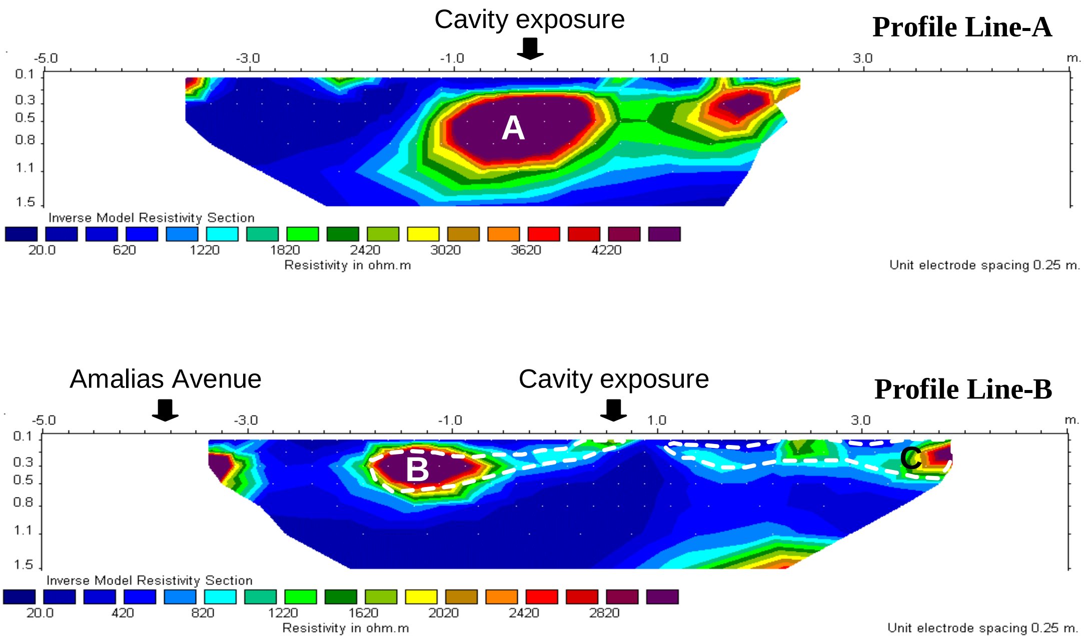


FIG. 8. 2D resistivity images of profiles Line-A and Line-B.

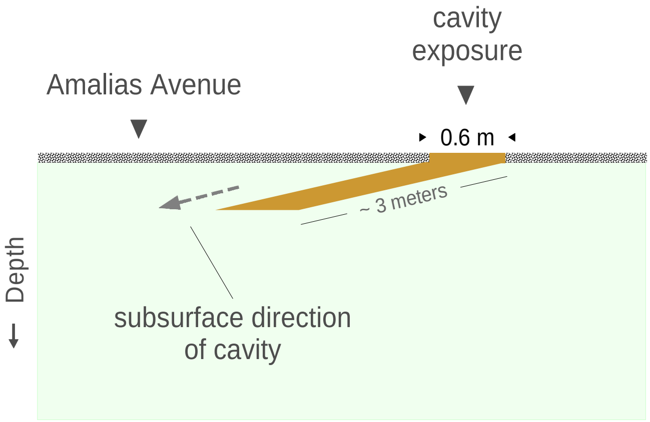


FIG. 9. Sketch diagram of the exposed cavity characteristics as they were measured in the field.

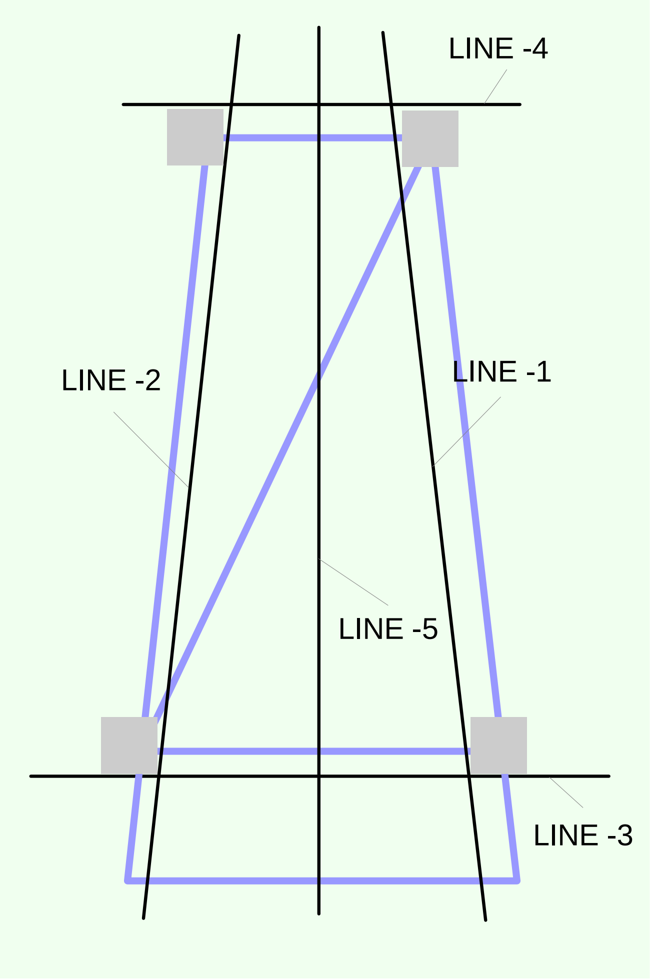


FIG. 10. Profile lines acquisition pattern.

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 0.3 m electrode spacing) gave no major differences on the inversion results the 0.3 m spacing was chosen for the whole survey because it reduces the acquisition time without significant loss in the resolution of 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.

These numerical comparisons also showed that a data set with intermediate random noise level could give high-resolution images depending always on both the data density and the depth of the prospect.

By summarizing, the synthetic modelling indicated that 0.2 m is the optimal electrode spacing to delineate the specific targets having sharp contrast in comparison with the host medium. However the efficient spacing of 0.3 m was chosen to speedup the fieldwork with no significant loss in resolution. While the background resistivity values were recovered well enough, the resistivity values of the recovered target were lower than the actual ones. Especially, the resolving power decreases by increasing 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 represented by a resistivity variation of 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 and thus making the target discrimination difficult.

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

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 exposed cavity (Fig. 9).

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 exposed cavity, all circumstances are satisfied to interpret the high resistive block C as an indication of unknown cavity.

DATA ACQUISITION AND PROCESSING

The data were acquired on four lines namely, LINE-1, LINE-2, LINE-3 and LINE-4 (Fig. 10) over three placement sites C, D and F by using the electrical tomography method of Wenner-Schlumberger array with a maximum N separation (ratio of maximum and minimum electrode spacing) that equals to 12. In placement site E, an extra line namely LINE-5 was added (Fig. 10) between lines LINE-1 and LINE-2. The data collection was performed by the SYSCAL R1 Plus resistivity meter (IRIS).

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 distribution. The true resistivity structure was interpreted using 2.5D smoothness constrained algorithm to invert the apparent resistivity data (Tsourlos, 1995; Tsourlos *et al*., 1998). A quasi-Newton technique was employed 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 should be minimum.

RESULTS – INTERPRETATION

The inverted resistivity sections set up a pseudo 3D configuration according to their layout patterns (Fig. 10) that are shown in Figures 11, 12, 13 and 14. As it can be observed from the data, the investigated area shows complex geophysical patterns with variable range of resistivity values. 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 resistive 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.

The synthetic modelling 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.

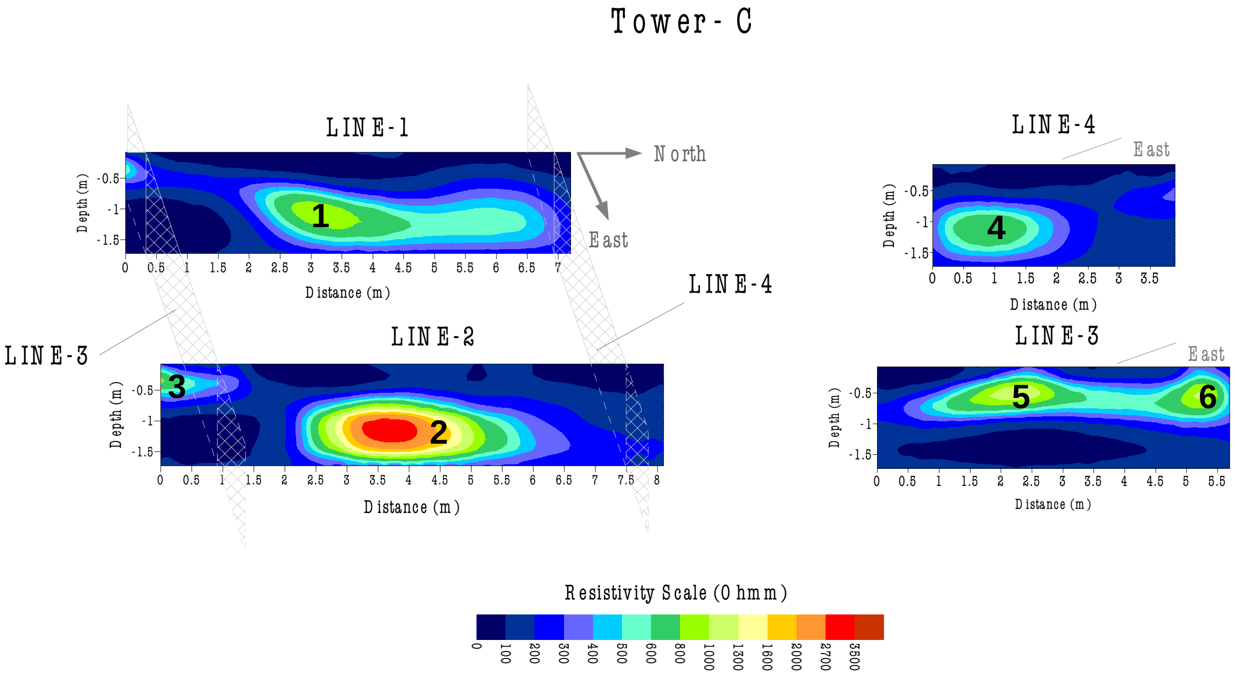


FIG. 11. 2D resistivity tomograms in the placement area of tower C.

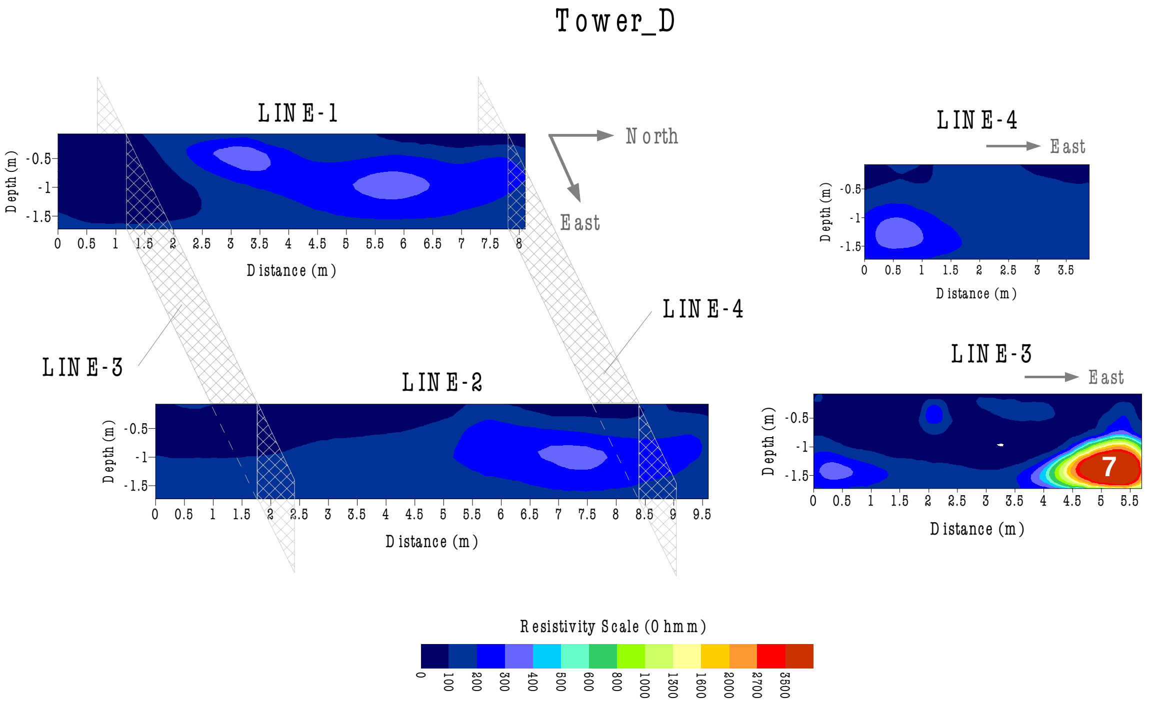


FIG. 12. 2D resistivity tomograms in the placement area of tower D.

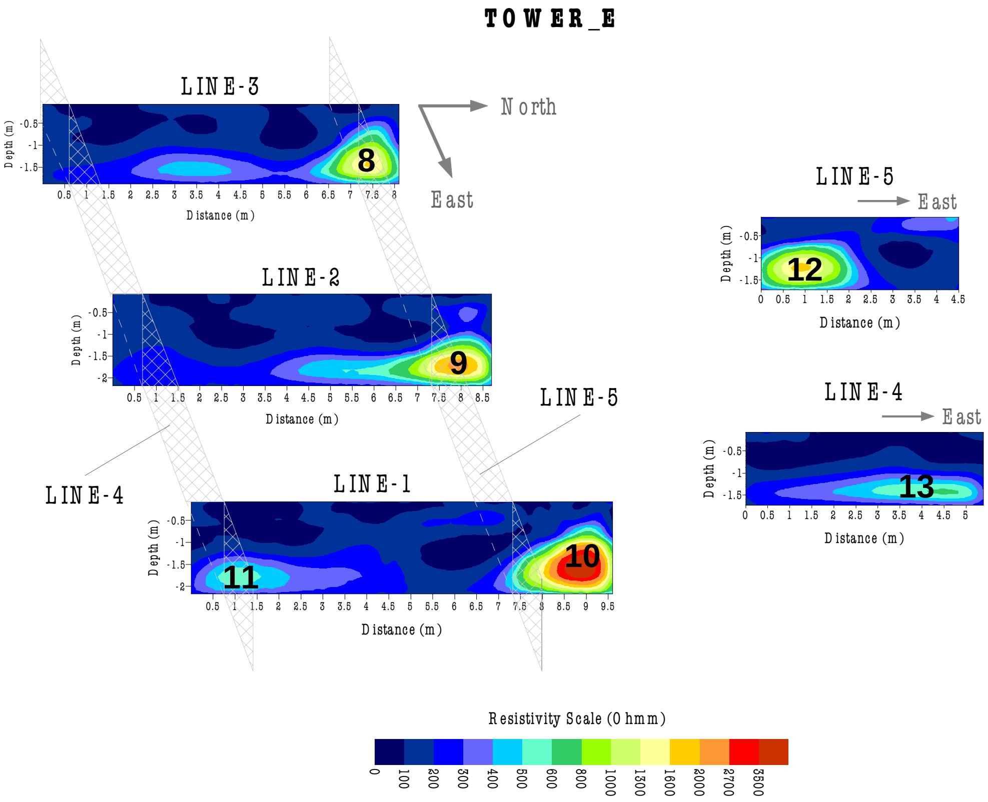


FIG. 13. 2D resistivity tomograms in the placement area of tower E.

Thus, across tower C (Fig. 15), the rectilinear feature (**c2**) with orientation E-W and having dimensions of 1 m in diameter and 4m in length, detected at 1 m depths, is attributed to a cavity. The rectilinear features (**c1**) and (**c3**) with dimensions 0.6 m in diameter and respective lengths and depths of 1.5 m, 1 m and 4.5 m, 0.3 m 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.

In view of the 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 a nearby stream (Heridanus River?) whose trace passes close to the eastern boundary of the temple. 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 and the full extend of this drainage system remained unclear.

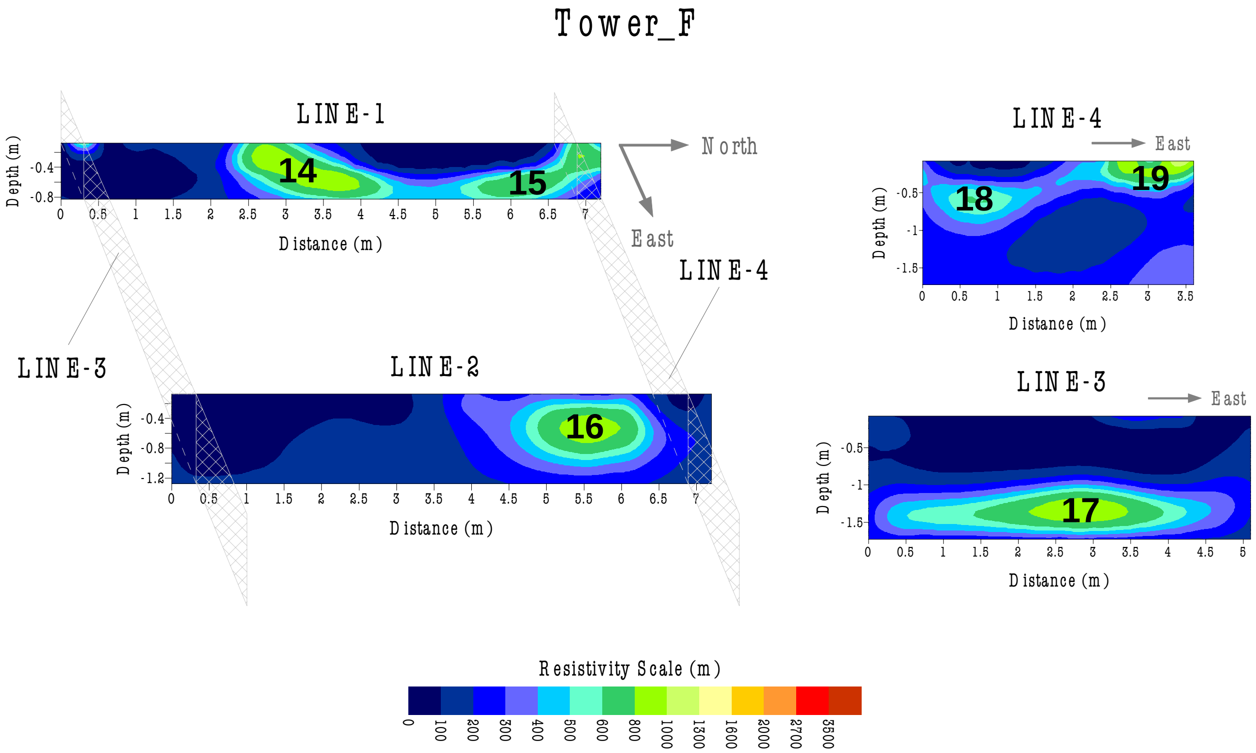


FIG. 14. 2D resistivity tomograms in the placement area of tower F.

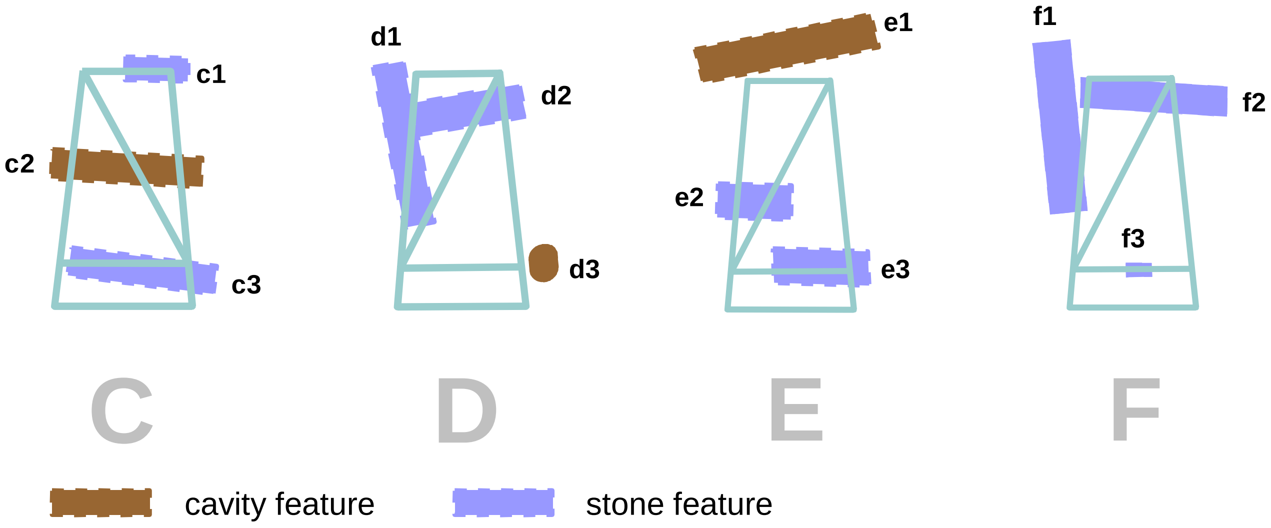


FIG. 15. Interpreted features.

CONCLUSIONS

The sparse distribution of the investigated sites limited the reliable interpretation of the geophysical response 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 resistive anomalies which are strong indicative of artificial features. Some of them are attributed to cavities, which produce very high resistive anomalies and are more likely to represent relics of an ancient underground conduit system while others (although difficult to interpret precisely) more likely to represent archaeological features such as stone walls or relics of column drums. Unfortunately the results are not sufficiently 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 resistive anomalies only look well-defined if they cross through areas of lower background resistivity. This seems to suggest that the lower resistive areas have been disturbed or intersected by the construction of the features that have caused the high resistive 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.

The geophysical survey results were positive from the site characterization point of view. Three sites with strong indications of underground cavities were identified, 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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REFERENCES

Dahlin, T., 1996. 2D resistivity surveying for environmental and engineering applications: First Break, **14**(7), 275-283.

Loke, M. H., and Barker, R. D., 1994. Rapid least-squares inversion of apparent resistivity pseudosections: Extended Abstracts of Papers 56th EAGE Meeting Vienna, Austria 6-10 June 1994, p. 1002.

LaBrecque, D., Miletto, M., Daily, W., Ramirez, A., and Owen, E., 1996. The effects of resistivity tomography data: Geophysics, **61**, 538-548.

Louis, I. and Papadopoulos, T., 2001. Geophysical Site Assessment at the Ancient Temple of Olympian Zeus in Athens: Technical Report, part B (towers C, D, E and F), Athens.

Oldenburg, D. W., and Li, Y. G., 1999. Estimating depth of investigation in dc resistivity and IP surveys: Geophysics, **64**, 403-416.

Noel, M. and Xu, B., 1992. Cave detection using electrical resistivity tomography: Cave Science 19, 91Ð94. Sensors and Software, Inc (1996), Pulse Ekko Tools User Guide Version 1.22. Technical Manual 22.

Tsourlos P., 1995. Modelling, interpretation and inversion of multielectrode resistivity survey data: Ph.D. Thesis, University of York.

Tsourlos P., Szymanski J., and Tsokas G., 1998. Smoothness constrained algorithm for the fast 2D inversion of DC resistivity and induced polarization data: Journal of the Balkan Geophysical Society, **1**, 3-13.

WEB SITES FOR GENERAL INTEREST

http://lilt.ilstu.edu/drjclassics/sites/athens/OlympianZeus/lecture.htm

http://www.vangelis.myweb.nl/mythodeagallery.htm