Imaging of ancient water management infrastructures through 3-D Electrical Resistivity Tomography: The case of Eleutherna archaeological site (Crete, Greece)

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Abstract

Water resources and their efficient management though specialized hydraulic construction works comprise the basic guide in each human activity and the main criterion for the selection of a permanent residence. This work describes how geophysical methods can be used in order to map such hydraulic structures enlightening at the same time past and completely unexplored archaeological hypotheses. To this direction a high resolution surface 3D ERT survey was completed at the site of *"Anemomylos" on the hill Pyrgi, the Acropolis of* Eleutherna in Central Crete (Greece). The analysis and the 3D inversion of the data revealed the existence of a new structure that is either a cistern or a basin to the management of water. This lies between the aqueduct tunnel and the two existing cisterns verifying a past archaeological hypothesis.

Introduction

Ancient Eleutherna (Fig. 1a) is located about 25 Km south-east of the city of Rethymno at the northern foothills of Mount Ida (Crete, Greece). It is one of the most important Cretan urban centers with a constant occupation spanning from Geometric-Archaic up to early Byzantine era. University of Crete has been systematically excavating at the site since 1985.

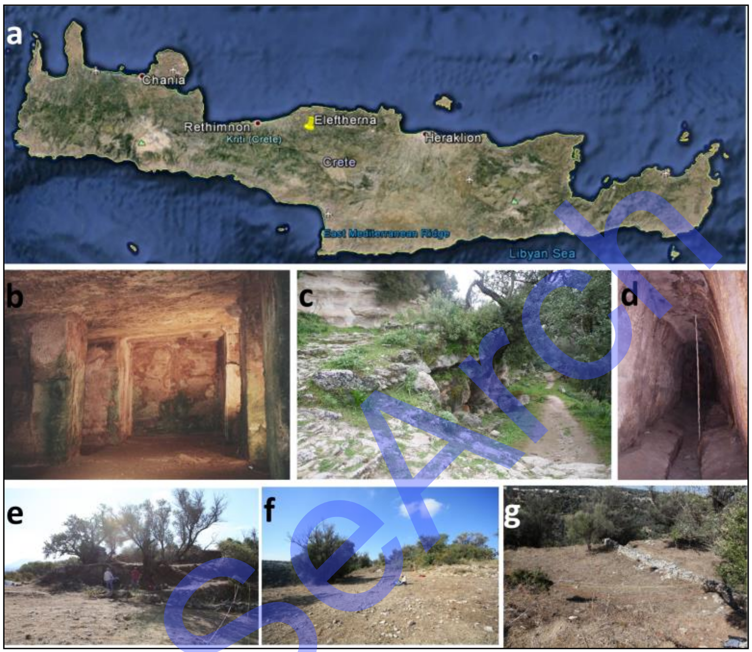

Figure 1: *a) Google Earth satellite image of Crete with the location of Eleutherna; b, c) View of the interior and the entrance of cistern 1; d) The roman aqueduct tunnel as it is seen from its entrance; e, f, g) Views of "Anemomylos" site where the ERT survey was conducted from north, south and east.*

The excavation of Sector II at the hill Pyrgi has shown that it served as the Acropolis and the city center throughout the centuries, from the Ancient to Byzantine era. The ancient temple discovered on the central plateau of the hill was constructed in the 7^{th} century BC, but remained in use until the 2^{nd} century AD. Just in south of the temple a public bath complex of the roman period has been excavated (Tsigonaki, forthcoming). In most cases the construction of roman baths is combined with the construction of an aqueduct. The two rock-cut cisterns, further to the south, on the west slope of Pyrgi hill (Fig. b, c) and the tunnel of an aqueduct (Fig. 1d), whose entrance is located at the east slope at the nearby site called "Anemomylos", are the two landmarks on the Acropolis. Both of them constituted the most important infrastructures of Eleutherna, related to the water resources management of the ancient city. The first systematic mapping of the cisterns and the tunnel was undertaken by Dinu Teodoresku and Max Guy in 1993-1994. The following years, some limited excavation works in the cisterns were unsuccessful in solving the problem of the dating of their construction. However the study of pottery enhanced the evidence that they were still in use during the 7^{th} century A.D.

The cisterns were dug into the marly limestone and cover a total area of about 800 square meters. Their maximum combined capacity is estimated to 5,500 cubic meters of water. The tunnel is located about 45-50 meters to the north and along the same direction of the cisterns (Fig. 2). It is rock-cut, vaulted with a central channel. The mean burial depth of the top of the tunnel with respect to ground surface is 8 meters. The tunnel's dimensions vary between 2-3 m height and 2 m width at its bottom. Its dimensions are similar to those of the aqueduct of Elyros (West Crete). It is also larger in section than other tunnels in Greece, such as the Hadrianic aqueduct of Corinth (Lolos 1997, 301). The tunnel at Anemomylos is 40 meters long and ends to a transverse well-built wall, which reminds of a fountain frontage. A small hole at the half of the wall's height was used for the flow of water through a clay pipe, at least 4 meters long that seems to be directed towards the cisterns. The long distance between the aqueduct and the cisterns advanced the hypothesis of the existence of a third cistern that has not yet been revealed (Kalpaxis 2004, 111-112).

Scope of the work

Geophysical methods can provide a non-invasive alternative within the archaeological research in mapping buried structures related to ancient water infrastructures. Bavusi et al (2004) reported a multidisciplinary geophysical approach with gradiometry, HVSR (Horizontal to Vertical Spectral Ratio) and GPS techniques to map a Roman aqueduct. An effort was made by Brinon and

Kessouri (2009) to understand the pattern of the hydraulic system in a karstic environment through electromagnetic and magnetic techniques. The potential of ERT method to map Qanat systems (series of vertical shafts connected by gently sloping tunnels) was investigated by numerical simulations and a real example from Iran (Ghanati and Hafizi, 2012). Diverse imaging methods (VLF, ERT, TEM) were employed over the known location of Roman aqueduct to test their resolution capabilities, however with controversial results (Trogu et al., 2014). More recently, Gorokhovich et al. (2014) employed GPR and TEM to discover potential subsurface targets that could be related to the remnants of a water supply structure in Crete.

Nowadays the archaeological research of the water management in Eleutherna seeks to find valid explanations on specific problems related to: a) the mechanism of the water filling of the cisterns, b) the way the water was distributed to the ancient city and c) the relation, if any, between the cisterns and the aqueduct tunnel.

Field survey

Based on the above problematic, a high resolution three-dimensional (3-D) Electrical Resistivity Tomography (ERT) was employed at the site of *"Anemomylos"* in an attempt to approach these basic but still unanswered scientific questions, emphasizing mainly on the relation among the cisterns and the aqueduct tunnel. The 3-D ERT method was selected to meet the specific needs and the challenges of the survey in the archaeological site of Eleutherna, rising mainly by the uneven topography (Fig. 1e, f, g) and the physical properties of the potential targets (resistive signature). The specific goals for the geophysical investigation were twofold: a) to identify the possible continuation of the aqueduct tunnel towards the cisterns and b) to investigate the hypothesis related to the existence of a third cistern between the tunnel and the existing ones.

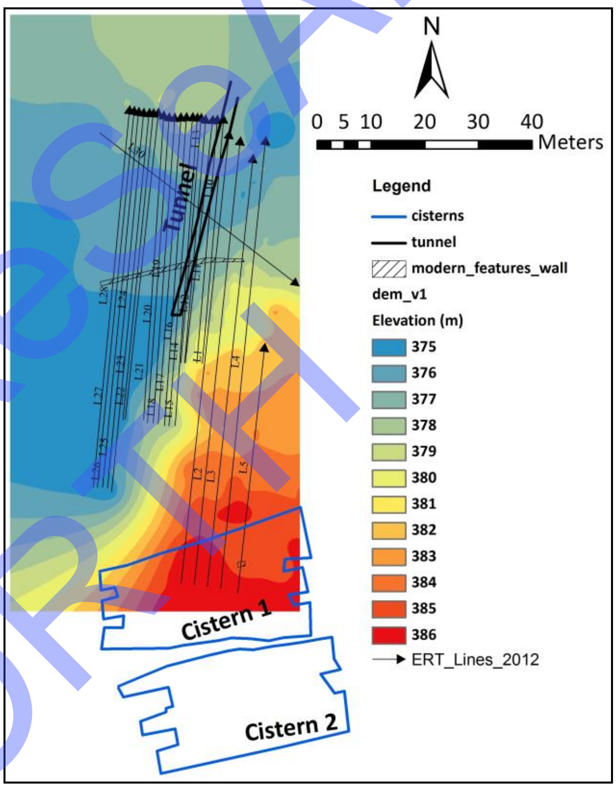

Figure 2: *Digital elevation model of "Anemomylos" area where the location and direction of the ERT lines has been superimposed. The line numbering starts form the west (L28) and decreases towards the east.*

The geophysical survey covered a total area of more than 1,900 square meters employing the 3-D ERT method (Fig. 2). Originally a rectangular grid was established with a total station instrument in order to help the systematic layout of the individual 2-D ERT lines. An effort was made to keep a parallel distance of 1 meter between lines L28 to L1 and 2.5 meters between L1 to L5 as we move from west to east at the site. Unfortunately this was not always accomplished since in situ large obstacles (rocks) prohibited their regular layout in some cases. Totally the area was covered with 25 lines with variable length oriented in the SW-NE direction. The dipole-dipole array was utilized to collect more than 42,500 apparent resistivity data along all the lines with a multi-channel resistivity instrument, using multiple combinations of spacings (a) and N separations (1a, 2a, 3a, 4a and Nsep =10a, a=1m the unit electrode spacing along each line).

The coordinates of more than 240 randomly scattered ground positions, were mapped through a hand held GPS system. The raw GPS data were post-processed in a differential mode in order to accomplish a final positioning accuracy of less than 30cm. The corrected GPS data formed the basis for the compilation of the digital elevation model (DEM) of the site that shows a systematic elevation drop from 386 meters at the south east to 375 meters towards the north and the east (Fig. 2).

ERT data processing and results

Almost 8% of the original apparent resistivity data were filtered due to poor electrode contacts. Since the positions of the electrodes cannot strictly fit into a simple rectangular grid, the model grid specifying the boundaries of the model blocks was made independent of the positions of the electrodes. Commercial software (Loke and Barker, 1996) was used to model and invert the apparent resistivity data in an attempt to reconstruct a 3-D subsurface resistivity model. The topography information (extracted by the DEM) of each one of the 1537 electrodes was incorporated within the modeling and inversion procedure. The finite element method was used to solve the forward resistivity problem. A homogeneous half-space was used as initial model to start the inversion procedure and an iterative smoothness constrained Gauss-Newton optimisation routine (deGroot-Hedlin. and Constable, 1990) was implemented for recovering the subsurface resistivity of more than 50,000 3-D model parameters.

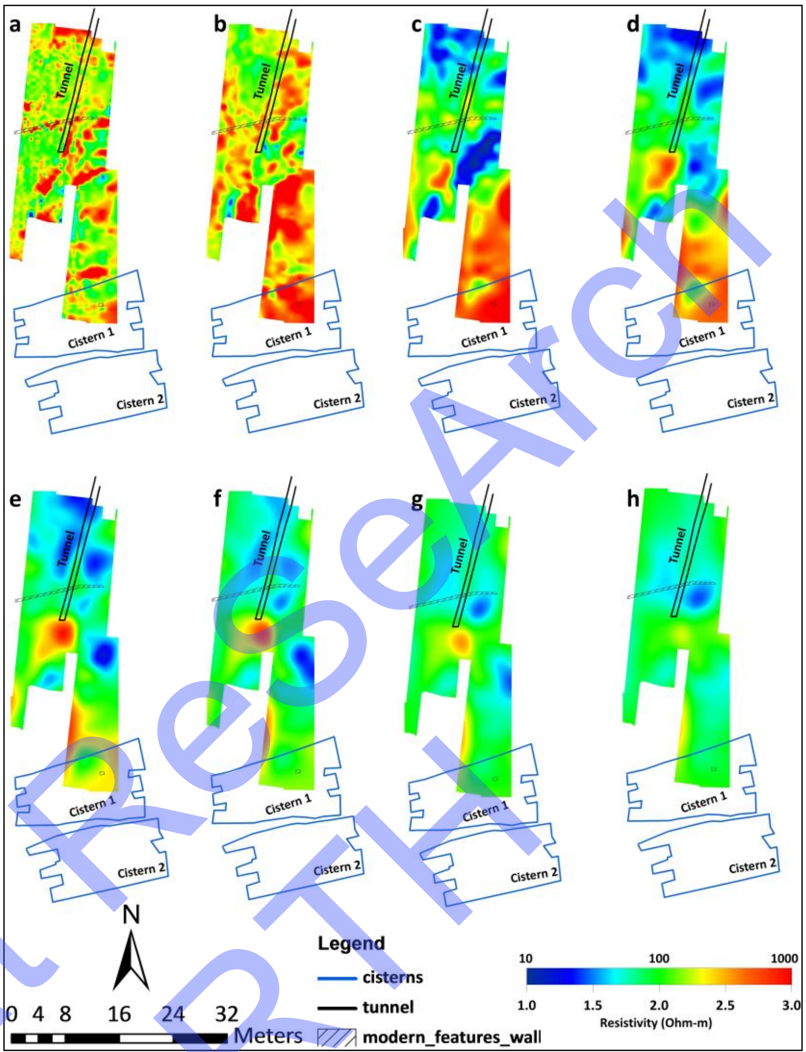

Figure 3: *Horizontal depth slices that were extracted from the 3-D resistivity inversion model (6 iterations, RMS=4.4%): a) z = 0-1m, b) z = 1-2m, c) z = 2-3m, d) z = 3-4m, e) z = 4-5m, f) z = 5-6m, g) z = 6-7m, h) z = 7-8m.*

Horizontal slices from increasing depths every one meter (Fig. 3) were extracted from the 3-D volumetric resistivity model and overlaid on the topographic map of the area in an effort to spatially correlate the high amplitude resistivity anomalies with respect to the location of the cisterns and the aqueduct tunnel. Up to the depth of two meters below the ground the subsurface shows substantial inhomogeneity with scattered high resistivity anomalies (Fig. 3a, b). This image can be justified by the anthropogenic layer that has been deposited in the area due to the constant use of the site during the centuries. Furthermore the abrupt elevation variation as we move from south to north has definitely affected the measurements within the first layers, which is registered with increased resistivity signatures. As we move to the deeper layers (after the depth of 2 meters – Fig. 3 c-h) the subsurface starts to have a more conductive signature. This signifies the existence of marl to marly limestone layer which is actually the material where the tunnel and the cisterns have been dug into.

The most prominent resistivity anomaly makes its appearance three meters below the ground surface and reaches up to the depth of seven meters (Fig. 3d-g). It has an ellipsoidal shape and is oriented along the SW-NE direction. In its full extend the long and the short axis of this anomaly is 11.5 m and 5 m respectively. The most important observation lies on the fact that this area is aligned with the direction of the tunnel and actually it appears after the ending point of the pipe that reaches the wall of the tunnel. The shape, the orientation and the dimensions of this high resistivity area can suggest the existence of a structure located between the tunnel and the two rock-cut cisterns. This is probably a cistern or a basin belonging to the same hydraulic system and related to the management of water. Further archaeological investigation will enable us to define the exact form and use of this structure.

Discussion and Conclusions

The management of water resources relies on the design and implementation of efficient storing (e.g. cisterns, wells) and transportation (e.g. tunnels, Qanats, aqueducts) hydraulic construction works. A number of archaeological and historical records reveal the significance of the past water management techniques, which are also met in modern scientific branches of water resources. The extensive historical and archaeological study of the diverse water management practices, especially within a regime of intense environmental and climatological challenges (e.g. droughts, floods), is extremely important in enriching the modern practices for the efficient management of the limited water resources. To this direction geophysical prospection methods can be used for the mapping of such buried structures while at the same they provide the technological means for testing past archaeological hypotheses that have remained completely unexplored for years.

Acknowledgements

This work was performed/conducted in the framework of the POLITEIA research project, Action KRIPIS, project No MIS-448300 (2013SE01380035) that was funded by the General Secretariat for Research and Technology, Ministry of Education, Greece and the European Regional Development Fund (Sectoral Operational Programme : Competitiveness and Entrepreneurship, NSRF 2007-2013)/ European Commission.

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