Archaeological Investigations in Urban Areas through Combined Application of Surface ERT and GPR Techniques

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Abstract: Among the geophysical methods, Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) comprise the most promising techniques in resolving buried archaeological structures in urban territories. In this work, two case studies which involve an integrated geophysical survey employing the surface three dimensional (3D) ERT and GPR techniques, in order to archaeologically characterize the investigated areas, are presented. Totally more than 4000 square meters were investigated from the test field sites, which are located at the centre of two of the most populated cities of the island of Crete, in Greece. The ERT and the GPR data were collected along dense and parallel profiles. The subsurface resistivity structure was reconstructed by processing the apparent resistivity data with a 3D inversion algorithm. The GPR sections were processed with a systematic way applying specific filters to the data in order to enhance their information context. Finally, horizontal depth slices representing the 3D variation of the physical properties were created and the geophysical anomalies were interpreted in terms of possible archaeological structures. The subsequent excavations in one of the sites verified the geophysical results, enhancing the applicability of ERT and GPR techniques in the archaeological exploration of urban territories.
Keywords: urban areas, archaeological structures, ERT, GPR

1. INTRODUCTION

The inevitable necessity of developing modern urban infrastructures (roads, buildings, pipelines e.t.c.), in combination with the extensive construction works that accompany them, may threaten important archaeological monuments, which are still buried in the subsurface of the urban territories. The need of the effective and early detection of these cultural remains has motivated the use of the geophysical techniques in the archaeological exploration of urban areas (Lück *et al.*, 1997).

The Ground Penetrating Radar (GPR) and the surface Electrical Resistivity Tomography (ERT) appear to be the most suitable techniques to archaeologically characterize the complex subsurface properties inside the urban areas, as they can provide a rapid, economic and non-invasive tool in the service of the archaeologists. Tsokas *et al*. (2008) used non-destructive ERT to investigate the area around and inside a church. Leucci and Nergi (2006) implemented the GPR method to map the subsurface archaeological features in an urban area. More recently Negri *et al*. (2008) evaluated the effectiveness of the integration of surface GPR and ERT techniques in researching archaeological items in a geologically complex subsurface.

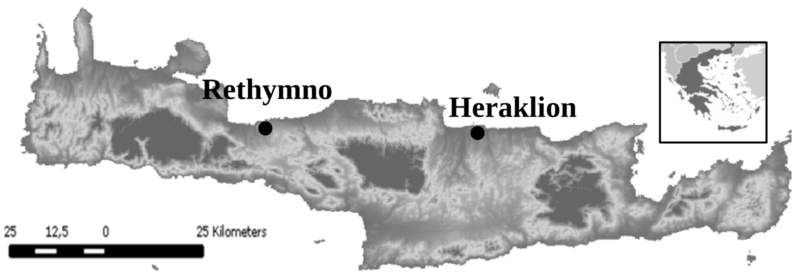

Fig. 1. Topographical map of the island of Crete, which is located at the south of Greece, where the Heraklion and Rethymno cities at the north cost side of the island can be seen.

In this work, the successful results of the combined geophysical prospection employing both GPR and ERT methods from two different urban territories are presented. The test field sites are located in two of the most populated cities (Heraklion and Rethymno) of the island of Crete in Greece (Fig. 1). The historical route of the Heraklion city begins from 7000 B.C. with the Knossos civilization and covers the entire spectrum of the greek history (Minoan, Byzantine, Venetian, Ottoman, Modern Times). In fact Heraklion acted as the capital city of the island of Crete and seat of administration which marked the town's image and character. Although Rethymno is less populated than Heraklion, a very similar historical background characterizes this city as well. As a result, a large number of historical and archaeological monuments can be observed in both cities revealing their rich historical and archaeological background. Apart from all these visible monuments, a large number of possible archaeological structures are still buried in the urban subsurface, which unfortunately may be threatened by the careless design and construction of the modern infrastructures.

A brief historical feedback concerning the field test sites is provided. Then the geophysical survey pattern employing the surface ERT and GPR methods and the various data processing stages are described. At last the geophysical anomalies detected in the ERT and GPR geophysical maps were interpreted in terms of possible buried archaeological features.

2. INVESTIGATED AREAS

Two different areas in the two cities of Crete were used as test sides. Bentenaki area is located along the north cost seaside at the central part of Heraklion city (Fig. 2A). The Saint Petros church is saved in the area and is extended to the west between the Sof. Venizelou and the Mistotaki avenues. During the restoration construction works along the seaside avenue, a paleochristian church was excavated. This church is believed that was constructed during the early byzantine times. It has frescos and inscription samples and seems to comprise part of a general construction complex, which its continuation is not obvious today.

The Turkish School (Fig. 2B) is a building in the old town of Rethymno where today it functions as an education institute and accommodates the 1st elementary school of Rethymno. An inscription at the west entry of the school reports that it was built in 1796 and functioned as school of girls. It has eleven teaching rooms and an impressive Turkish style entry.

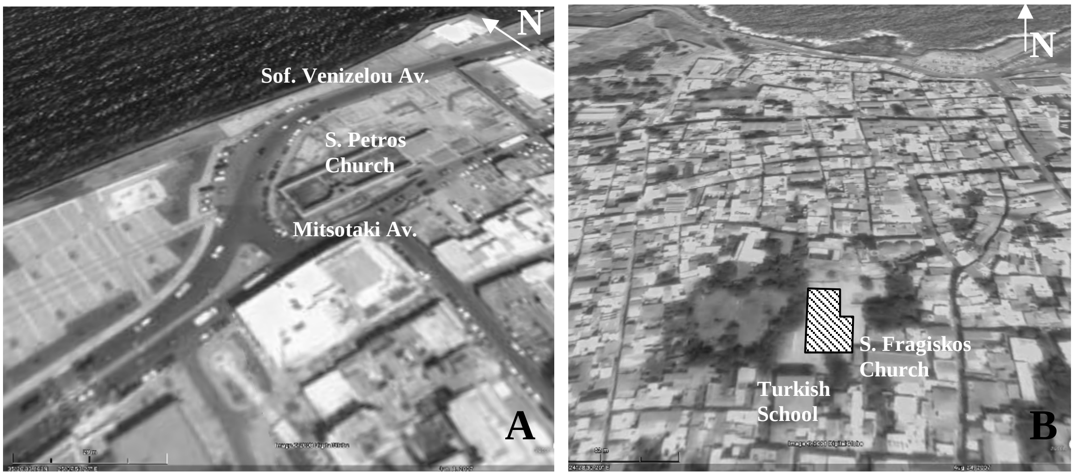

Fig. 2. A): Panoramic view of the area Bentenaki in the city of Heraklion. The surveyed area can be seen along the Sof. Venizelou Avenue. B) Satellite image of the old town of Rethymno, where the investigated area is located at the north of the Turkish School facilities (hatched rectangular).

3. FIELD METHODOLOGY

The surface Electrical Resistivity Tomography (ERT) and the Ground Penetrating Radar (GPR) methods were chosen as the most appropriate techniques to conduct the geophysical investigations, according to the local environmental conditions (urban territory) and the complex background nature where possible archaeological remains may be buried in. The ERT data were collected in terms of dense parallel two dimensional (2D) sections along a single direction. This specific survey mode can guarantee the accurate 3D mapping of the possible buried archaeological structures (Papadopoulos *et al.*, 2006). A similar survey mode was followed for the GPR data as well, which were collected along parallel transects, forming a specific grid. A multichannel resistivity instrument (SYSCAL Pro Switch 96) was used to collect the apparent resistivity data, while the NOGGINPLUS unit with the 250 MHz antennas was used for the GPR survey.

At the Bentenaki area in Heraklion city, the geophysical investigations were conducted along the Sof. Venizelou Avenue until the intersection with the Mitsotaki Avenue (Fig. 2A). Due to the urgent construction works that are carried out in the region for the restoration of the seaside avenue, the area was mostly covered with the GPR technique. The field work was completed in twelve hours during the afternoon of 29th until the morning of the 30th May 2008. A total area of more than 2000 square meters, divided in seven individual grids was investigated, along dense parallel profiles. Similar data collecting parameters were used for all the profiles. The inter-line spacing was 0.5 meter and the spacing interval along each profile was 0.025 meters. The goal was to cover as much region as possible, but surface obstacles like ditches, pipe lines and parked cars at the side of the avenue hindered the maximum coverage of the area. A specific area of more than 450 square meters at the north of the Sof. Venizelou Avenue was also approached with the ERT method. The purpose of the ERT survey was to enhance the information context obtained with the GPR data. Totally ten parallel 2D tomographies were measures employing the pole-dipole configuration. Half of them had a length equal to sixty (60) meters while the length of the remaining five lines was thirty five (35) meters. The inter-line and the inter-electrode distance was set equal to one meter and the measurements were taken with $a = 1$ m and $Nsep = 10a$ (a = electrode spacing, $Nsep$=maximum separation between the current electrode and the potential dipole). Some extra measurements with different combinations of a and $Nsep$ parameters were also measured in order to increase the vertical and horizontal area coverage. Bentonite contact electrodes were used in order to insert the electrical current in the ground (Athanasiou *et al*., 2007).

The more than 2000 square meters of the Turkish school yard at the north of the building facilities (Fig. 2B) were covered in a systematic way and the field work was completed in totally four days within August of 2006. Forty four (44) parallel 2D electrical tomographies along the south-north direction were measured employing the dipole-dipole configuration. The maximum length of each tomography varied from 20 to 76 meters, according to the available space. The basic unit inter-electrode spacing along all lines and the inter-line distance was one meter (a =1). All the apparent resistivity data with a=1 m and maximum separation between the current and potential dipoles $Nsep$ = 6 m were collected along each 2D line. Some additional data corresponding to2a, 3a distances for the current and potential dipoles were also gathered in order to maximize the information context and the resolution of the final resistivity model. Unfortunately it was not possible to use contact electrodes in order to minimize the field time as the school yard covered with asphalt. So the metallic electrodes had to be fixed in small holes that they were opened in the asphalt using a pneumatic drill. In order to ensure the good contact of the electrodes with ground salty water was poured within each hole and finally contact resistances of less than 3 KOhm were encountered. Exactly the same area was covered by a dense grid of parallel lines spaced 0.5 meters apart employing the GPR technique. Totally eighty eight (88) lines were collected and the sampling interval along each line was 0.05 meters. The flat ground of the investigated area contributed to gathering GPR data of high territorial resolution.

4. PROCESSING AND RESULTS

4.1 Data Processing Stages

The ERT and GPR data that collected from the two field sites were processed in a systematic way. At first despiking filters were applied to each one of the 2D tomographies in order to remove the extreme noisy apparent resistivity measurements. Almost 5% of more than the 33700 apparent resistivity data which collected from the area of the Turkish School were removed as outliers. The 3D apparent resistivity variation at the Bentenaki area in Heraklion was described by more than 10100 measurements. Due to the intersection of three 2D lines with a modern cement construction armed with steel, almost 4% of the original data had to be removed because of their unusual high or low values. Afterwards each one of the independent tomographies was given a relative coordinate according to a local reference system and the coordinate corrected lines were combined to a single file describing the 3D apparent resistivity variation from the two test sites. Finally a 3D resistivity inversion algorithm (Loke and Barker, 1996) was used to process the data, which is based on a Finite Element method for calculating the forward response of the resistivity model and an iterative smoothness constraint Gauss-Newton optimization method to reconstruct the true subsurface resistivity variation.

As far as the GPR data concerned, initially the first peak was determined in order to define the initial useful signal from each line. This determination was based on the intensity percentage of the first reflected wave (5-30%). The line equalization based on the selected first peak was followed and this procedure tried to bring the first reflections of each line in a common starting time. Then the application of AGC, Dewow and DCshift filters enhanced the reflected signal, while the rejection of the background noise and the data smoothing was accomplished by a trace-to-trace averaging filter. Finally horizontal depth slices at different depth levels were created by the original vertical sections assuming a velocity for the electromagnetic waves equal to 0.1m/nsec.

4.2 Bentenaki, Heraklion

The final processed GPR maps were georeferenced according to specific Global Positioning System (GPS) measurements and were overlaid on the Quickbird satellite image (resolution 60cm) of the area. The horizontal slices for the depth Z = 1.4-1.6 m of all the surveyed grids in the Bentenaki area are shown in Fig. 3A. The diagrammatic interpretation (Fig. 3B) of the strong subsurface reflections (warm colours) indicates an increased density of possible archaeological structures at the centre of the surveyed area and at the west and north-west of the Saint Petros church. Particularly the reflections at the central part of the area are probably related with the paleochristian church (Fig. 3A, B) that was recently excavated in the area. Since the strong GPR reflections seem to continue to the west of the paleochristian church for a distance of about 30-35 meters, this probably indicates that the church belongs to a broader architectural complex extending to that direction.

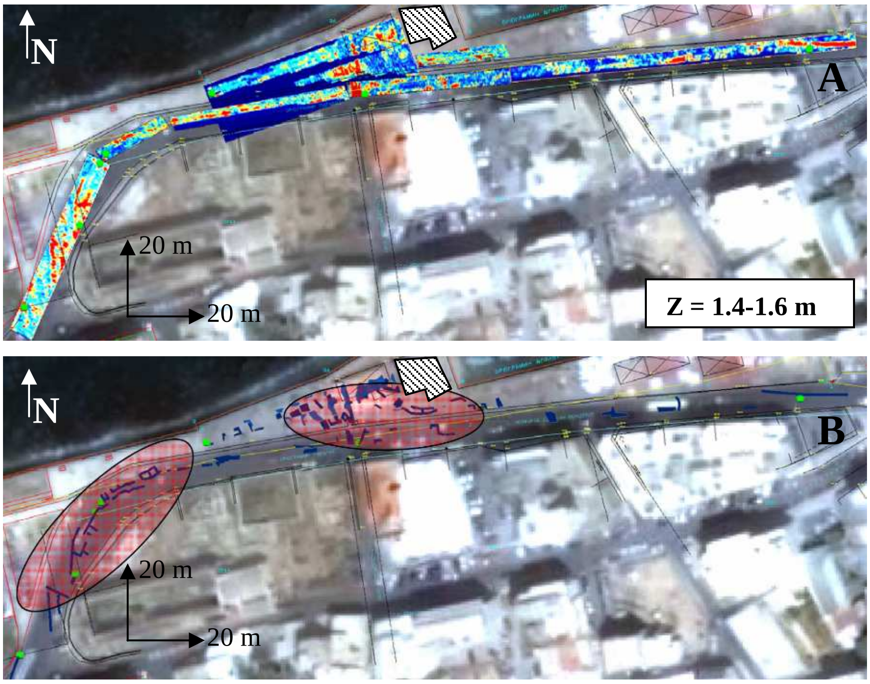

Fig. 3. A) Horizontal slice of the depth Z=1.4-1.6 m of the all the grids surveyed in the area Bentenaki in Heraklion. Warm colours indicate strong reflections. B) Diagrammatic interpretation of the major reflectors that are probably related to subsurface archaeological structures. The elliptical areas indicate the regions which exhibit the higher probability of archaeological structures be located. The hatched polygon indicates the position of the paleochristian church that was recently excavated during the construction works.

The 3D surface ERT survey that completed in a 400 square meters at the west of the paleochristian church contributed significantly in reconstructing the buried architectural structures. The 3D inversion algorithm converged to a 3D resistivity model after 5 iterations and RMS=7.77%. The model consisted of ten layers and 5400 resistivity parameters. Four parameters layers were extracted from the final inversion model and they are presented in the form of horizontal depth slices in Fig. 4. The horizontal and vertical extend of numerous interesting linear anomalies are located in the 3D resistivity inversion model, showing the pattern of the buried archaeological remains that are probably closely related with the recently excavated paleochristian church. The structures are buried 0.5 meter below the ground surface and seem to reach to a maximum depth of about 2.5 meters.

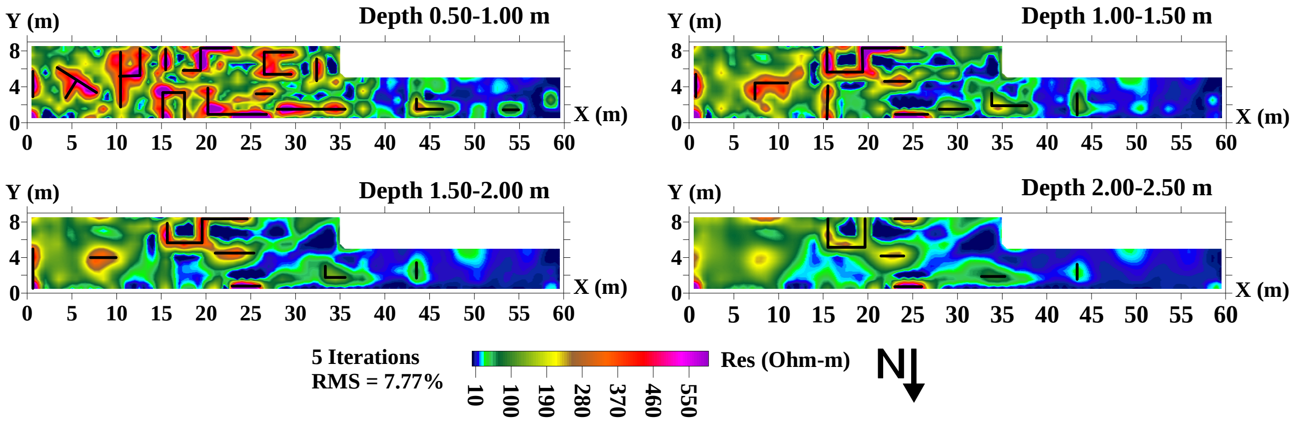

Fig. 4. Resistivity anomalies and their associated diagrammatic interpretation as resulted form the 3D resistivity inversion of the parallel 2D sections collected form the area of Bentenaki in Heraklion.

4.3 Turkish School, Rethymno

The resistivity inversion model from the area of the Turkish school consisted of 26144 parameters and eight layers. The 3D inversion algorithm converged to this subsurface resistivity model after 5 iterations with RMS=9.94%. Two horizontal slices for the depth Z = 0.7 m below the ground surface were extracted respectively from the 3D resistivity inversion model and the volumetric 3D GPR processed data (Fig. 5A, B). The combined diagrammatic interpretation of the detected GPR and ERT anomalies is presented Fig. 5C. Note that this map came from the integration of all the identified anomalies from all the horizontal depth slices from the GPR and the ERT final results respectively.

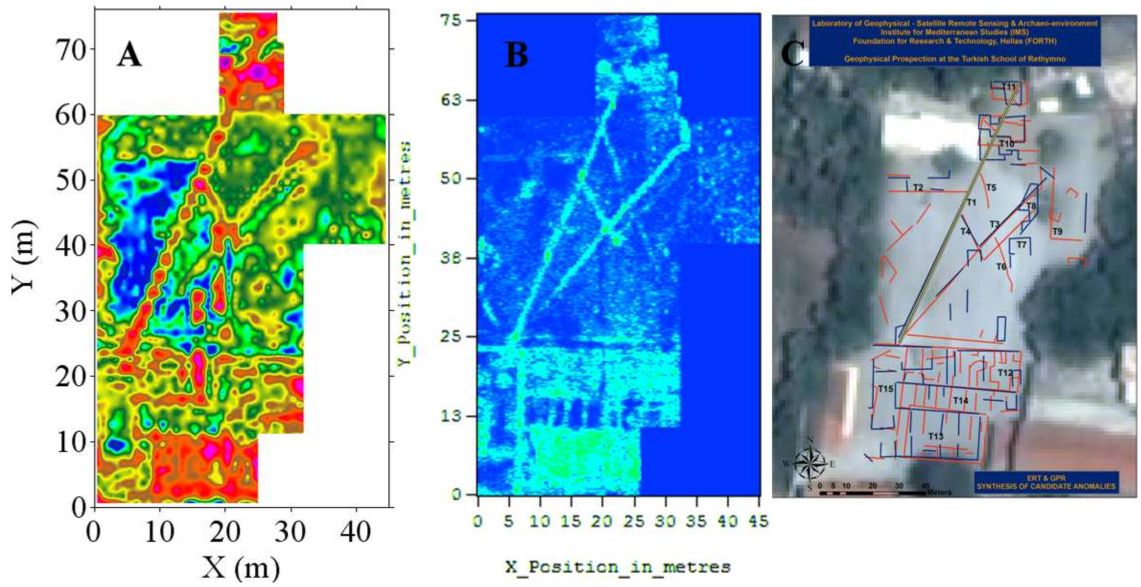

Fig. 5. Turkish School, Rethymno. A) Horizontal depth slice (Z = 0.7 m) extracted from the 3D resistivity inversion model (5 iterations, RMS=9.94%, resistivity dynamic range: 5-1000 Ohm-m). B) Horizontal depth slice (Z = 0.7 m) extracted from 3D volumetric GPR data. C) Combined diagrammatic interpretation of the ERT and the GPR geophysical anomalies. The warm colours indicate high resistivity values and strong reflectors.

It is obvious that mainly the south and secondly the north part of the area appear to be the most promising areas as far as the detection of buried archaeological structures concerned. At the north the anomalies T10 and T11 are related to architectural remains which are relatively compact and have N-S and E-W direction. The subsequent excavation revealed the buried structure that caused the anomaly T10 (Fig. 6A). It was proven that this archaeological structure did not form a regular shape which actually confirms the compact geophysical signature that was registered in the GPR and ERT maps.

At the south of the investigated area a number of archaeological remnants (anomalies T12, T13, T14 and T15) were located, which are probably related with the monastery of the Saint Fragiskos church. Specifically, the architectural structure T13 is extended to the west of the church and seems to have similar width with it. Furthermore these buildings are separated in different compartments with internal walls.

Finally the centre of the Turkish School yard is crossed by the anomaly T1. The subsequent excavations in the area proved that this anomaly is related to a drainage ditch or a rainwater pipe (Fig. 6B). This pipe is superficial, has a NE-SW direction and is probably a modern construction. Anomalies T2, T3 and T4 seem to be related with this specific pipe but they do not present a clear homogeneity.

Fig 6. A) Excavated structure at the north of the Turkish school area related with the anomaly T10. B) Modern drainage related with the anomaly T1.

5. CONCLUSIONS

The presented two case studies proved the efficiency of surface ERT and GPR techniques in the archaeological exploration of urban territories. The combined use of these methods and the integration of the final results seem to be adequate to reconstruct the complex subsurface material properties encountered in the urban areas and guide the archaeological excavation in selected places. The geophysical prospection methods through the application of these methods can effectively fill the gap between the construction development and the archaeological monuments preservation.

6. ACKNOWLEDGMENTS

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