Title:

Imaging of shallow underwater ancient ruins with ERT and seismic methods.

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Abstract
The present geophysical research aims in evaluating the applicability of the Electrical Resistivity Tomography (ERT) and seismic (Multichannel Analysis of Surface Waves - MASW and refraction) methods on mapping shallow underwater ancient remnants. The preliminary results from a single seismic line and its corresponding ERT section (surveyed at the site of Agioi Theodoroi area located 10 km eastern of Heraklion, Crete, Greece) are presented. This work demonstrates that ERT as well as MASW are very promising geophysical methods for the delineation of underwater antiquities. High resistivity anomalies were attributed to building walls and are in accordance with some of their mapped outcrops. Furthermore, MASW method exhibits significant correspondence with ERT showing lateral S-wave velocity variations at the positions where the high resistivity anomalies exist. Surface waves traveling through the shallow sediments (Scholte-waves) demonstrate relatively low velocity values. This makes them suitable for the detection of relatively large (> 0.5 m) underwater manmade structures, providing the use of a high frequency source and thus, the creation of relatively short wavelengths (< 2 m). These preliminary results show the potential in employing modern tomographic techniques in the revealing the cultural dynamics in shallow off-shore archaeological sites.

Main Objectives
The examination of ERT and seismic methods applicability in mapping shallow underwater ancient remnants.

New Aspects
Scholte-waves traveling through the shallow sediments demonstrate very low velocity values. This makes them suitable for the detection of relatively large (> 0.5 m) underwater manmade structures.

Type of Presentation
Prefer Oral but accept Poster

Topics
1. 06 Geophysics for Historical Heritage
2. 10 Marine Geophysics
3. 09 Seismic Surface Waves

Introduction

Electrical Resistivity Tomography (ERT) has been extensively used for the detection of ancient ruins in land. Fewer investigations aim on the detection of underwater structures (Passaro, 2010). On the other hand, high frequency acoustic methods (i.e. side scan sonar, sub-bottom profiler etc) are utilized for the detection of deep (i.e. 500 m) to shallow (i.e. 2 m) underwater antiquities, especially for shipwrecks buried in sediments (Plets et al., 2009, Grøn and Boldreel, 2014). Reports on using conventional seismic methods for mapping underwater ancient man made targets are rare or even non-existent.

The investigated area of Agioi Theodoroi Fig. 1) is located about 10 km east of the city of Heraklion in Crete, Greece and is known for a big four-side building excavated on the beach by Marinatos in 1926 (Marinatos and Hirmer, 1986). The specific excavation campaign brought to light some additional walls that were either covered by sea water or sand depending on the local conditions. Recent off-shore archaeological investigations managed to map the submerged archaeological relics that are buried at depth of less than one meter below the water sea level.

The aim of the presented geophysical research was to evaluate the applicability of the Electrical Resistivity Tomography (ERT) and seismic (Multichannel Analysis of Surface Waves - MASW and refraction) methods on mapping the shallow underwater ancient remnants. The complete geophysical survey consisted of two off-shore single 2D ERT lines in vertical directions, two grids laid out on the land and in the sea composed of parallel ERT lines for 3D mapping and one seismic line. However, in this work, only the preliminary results from the seismic line and its corresponding ERT section are presented. Apart from the geophysical survey, the outcrops of the residence walls were also mapped and high resolution air-photographs of the investigated area have been acquired. In addition, synthetic ERT data were created for the selection of the suitable acquisition parameters.

Geophysical data acquisition, processing and interpretation

The MASW method was applied along a line of 29.5 m total length. A Geospace MP-25 marine streamer, consisted of twelve 10 Hz hydrophones at intervals of 1 m, was submerged to the bottom of the sea for data acquisition. A 12 channel Geode seismograph, a 6 kg sledgehammer and a metallic plate were also utilized. A water-proof piezoelectric device was used for triggering. 36 records were acquired using the common shot array and the roll-along technique. The source interval was set to 0.5 m, resulting in 17.5 m Vs pseudo-section. Each record consisted of 2 merged shot gathers, 24 traces at intervals of 0.5 m and hydrophone length of 11.5 m. This was implemented by keeping fixed the source position while the streamer was moved on 0.5 m. When the hydrophone streamer reached at the centre of seismic line, seismic refraction data were also acquired with the source located at the following positions: 2 before the first, 2 after the last and 11 between the hydrophones. The ERT line, presented in this work, was surveyed using 33 electrodes equally spaced every 1 m, Syscal-Pro 10-channel resistivity meter, a multimode marine electrode cable and the dipole-dipole and pole-dipole arrays. For the pole-dipole array, one of the current electrodes was set at a distance of more than 150 m off-line, embedded in sea bottom. Both, floating and submerged electrode cable positions were tested for both ERT lines

For the processing of the MASW data the experimental fundamental dispersion curve of each record was selected amongst the local energy maxima on the frequency – phase velocity (f – c) domain using the kriSIS algorithms (Kritikakis et al., 2014). Dispersion curve values ranged from about 350 m/s at 35 Hz to 140 m/s at 70 Hz, resulting in surface wave (Scholte-waves) wavelengths from 10 m to 2 m, respectively. The dispersion curves were inverted using smoothness constraints and the resulted Vs depth profiles were set at the centre of the hydrophone spreads. According to Park et al. (2000), treating the Scholte waves as identical to the Rayleigh waves during the inversion analysis does not appear to significantly degrade the confidence level of the calculated Vs profiles. The distance between successive Vs profiles on the pseudo-section (Fig. 2) is equal to the source interval (0.5 m).

The first arrivals of seismic refraction data were picked and processed using the seismic tomography method (Fig. 3). The ERT data that collected using the floating electrode mode were inverted by the "DC2DPro" program (Kim, 2009), while the data collected using the submerged cable, with the "Res2DInv" program (Geotomo Software) (Fig. 4).

Four high resistivity anomalies (> 5 Ohm.m), attributed to manmade structures, were detected at 5.5 m, 12.5 m, 18.5 m and 26.5 m along the surveyed line (Fig. 4). The first three anomalies extend to absolute elevations greater than -2 m, while the fourth -1.5 m. The larger anomaly at 18.5 m coexists with the mapped outcrop of a building wall (Fig. 1). Seismic tomography results did not reveal any local target (Fig. 3). However, it shows a lateral variation of P-wave velocity at 18 m where the larger resistivity anomaly is also observed. S-wave velocity pseudo-section exhibits very low velocity values (< 150 m/s) at depth less than 1 m below the sea bottom (Fig. 2). Lateral velocity variations (> 150 m/s) within this low velocity layer are in accordance with the high resistivity values in geoelectrical section (Fig. 4). Higher S-wave velocity values (> 300 m/s) at depth grater than 2 m below the sea bottom (or elevations -2.5 m at S-SE to 3.0 m at N-NW) attributed to the bedrock. As shown in Fig. 4, the manmade structure (if really exists) detected at 26.5 m, does not seem to be founded on the bedrock.

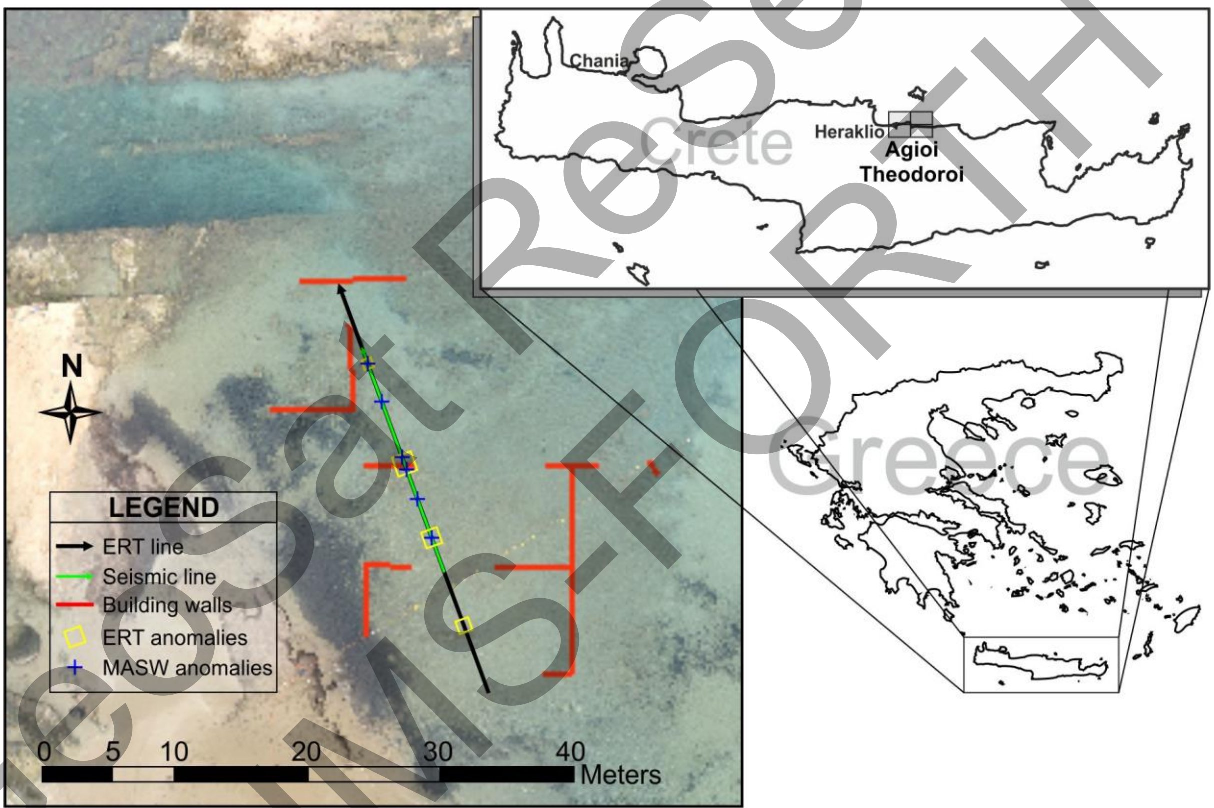

Figure 1 *The investigated area in Agioi Theodoroi, Crete, Greece.*

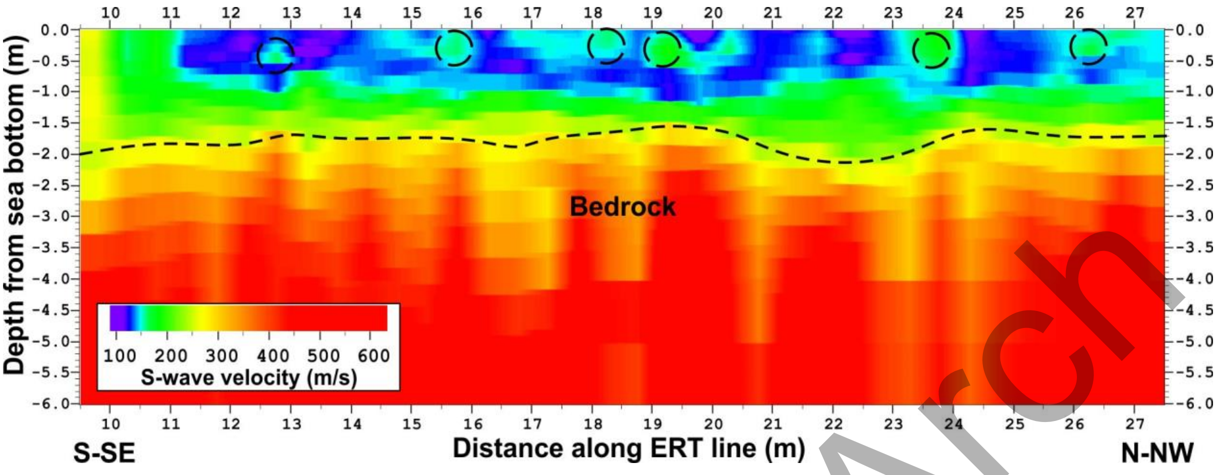

__Figure 2__ S-wave pseudo-section deduced from MASW. The locations of the circled velocity anomalies are also indicated on the map of Fig. 1.

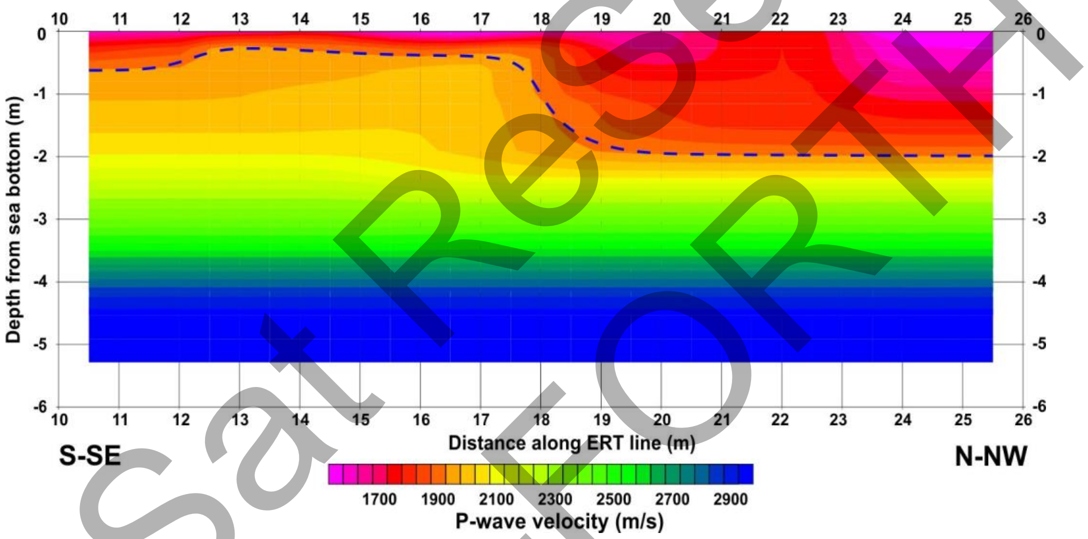

__Figure 3__ P-wave tomography section deduced from seismic refraction data (RMS error: 0.084 ms)

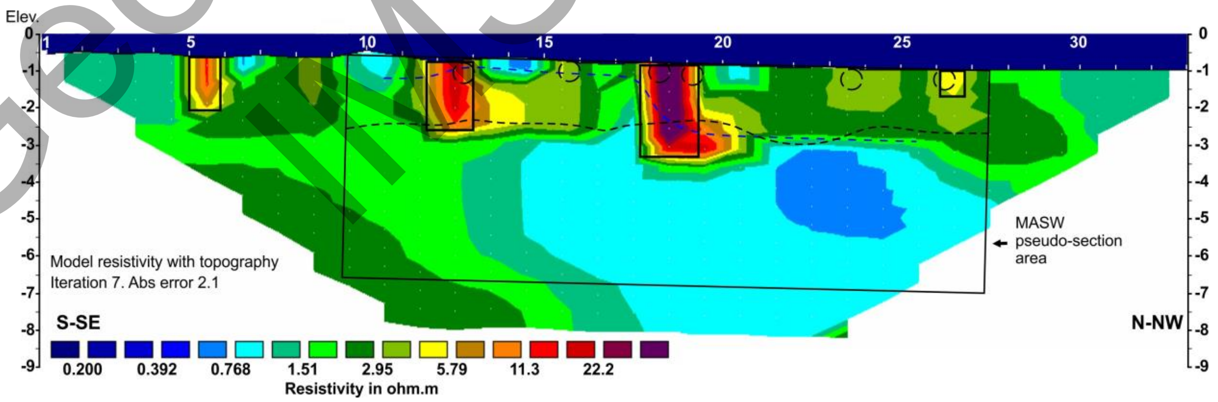

__Figure 4__ Geoelectrical section deduced from the robust inversion of ERT data using submerged pole-dipole array and Res2DInv software. Black and blue dashed curves were superimposed from the interpretation of MASW and refraction tomography sections, respectively. The locations of the squared high resistivity anomalies are also indicated on the map of Fig. 1.

Conclusions - Suggestions

This work demonstrates that ERT as well as MASW are very promising geophysical methods for the delineation of underwater buried ruins. High resistivity anomalies, which are attributed to building walls, are in accordance with some of their mapped outcrops. Furthermore, MASW method showed lateral S-wave velocity variations at the positions where the high resistivity anomalies exist. However, this does not guarantee that MASW anomalies deduced from the existence of underwater manmade structures. Further investigation about the validity of the extracted results must be performed. The depth of the bedrock has been extracted from seismic methods and compared to the depth of the building foundations.

Surface waves traveling through the shallow sediments (Scholte-waves) demonstrate very low velocity values. This makes them suitable for the detection of relatively large (> 0.5 m) underwater manmade structures, providing the use of a high frequency source and thus the creation of relatively short wavelengths (< 2 m). The use of hydrophone streamer and an automated seismic excitation (i.e. air-gun) may accelerate MASW method data acquisition. However, the poor lateral resolution and the intensive processing are significant drawbacks of this method.

Since the preliminary results of the MASW method were encouraged on the visualization of underwater buried ancient structures, synthetic models or/and controlled real data should be tested, not only for the verification of the presented results, but also to assist in the selection of the best acquisition parameters for the design of relative geophysical surveys.

Acknowledgements

This work was performed in the framework of the PEFYKA project within the KRIPIS Action of the GSRT. The project is funded by Greece and the European Regional Development Fund of the European Union under the NSRF and the O.P. Competitiveness and Entrepreneurship. This project comprises a collaboration between the Institute of Mediterranean Studies (Foundation for Research and Technology, Hellas) and the Ephorate of Underwater Antiquities (Ministry of Culture, Greece). The authors would like to thank Ephorate of UnderwaterAntiquities for its willing to secure the permission to conduct this survey as well as I. Moffat and N. Andronikidis for their assistant in data collection.

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