2023 IMEKO TC-4 International Conference on
Metrology for Archaeology and Cultural Heritage
Rome, Italy, October 19-21, 2023

Seismic refraction tomography and multichannel analysis of surface waves for imaging offshore Cultural Heritage in very shallow water: Results from a synthetic study and real data

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***Abstract* – In archaeology, applied geophysics helps to discover new findings of our hiden cultural heritage. However, these methods have been particularly developed in terrestrial environments, leaving the shallow marine ones almost unexplored. This paper examines the effectiveness of Multichannel Analysis of Surface Waves (MASW) and Seismic Refraction Tomography (SRT) on imaging submerged and buried antiquities in a very shallow marine environment. For this purpose, synthetic seismic data sets were created to examine the optimum parameters for the most efficient visualization and interpretation of shallow underwater buried man-made targets. The modeling results outlined that targets wider than 0.5m are reconstructed, both with the SRT and the MASW methods, provided that they are buried close to the seabed. In addition, short spread of the receivers with the MASW provided the most satisfactory outcome concerning the location of the submerged targets. In general the modeling results are quite encouraging and together with the succesfull application of MASW method in real data can form the basis for establishing the applicability of these geophysical methods in mapping submerged archaeological structures in shallow water environments.**

I. INTRODUCTION

The use of geophysical methods in the discovery of hidden archaeological structures, for the enrichment of our cultural heritage in a terrestrial environment, is nowadays established with numerous successful applications. However, coastal archaeological sites and related structures are endangered, due to climate change and rising sea levels. The dynamic and constantly evolving conditions in the coastal and shallow depth water zone have left much of the corresponding cultural heritage unexplored.

In the context of marine archaeology, the investigation of submerged archaeological sites has been made possible, through the use of 3D resistivity tomography methods [1]. Acoustic methods have been traditionally used to map ancient structures, shipwrecks and harbors [2], since they provide very high-resolution imaging, while multi-beam methods were utilized covering large areas for the visualization of seabed morphology and the classification of visible submerged man-made objects [3].

The high-resolution acoustic methods use reflected waves from the archaeological targets for their visualization. However, in the event of very shallow sea and buried targets, these waves are not easy to be distinguished from the direct ones. Thus, the main objective of this research is to propose a complementary and effective method for the mapping and visualization of buried structures of archaeological interest in very shallow waters. For this reason, this study focuses on seismic methods, such as Multichannel Analysis of Surface Waves (MASW) and Seismic Refraction Tomography (SRT), in which the seismic waves propagate along the seabed, and through the shallow buried targets, reach the receivers.

The effectiveness of the aforementioned seismic methods was initially examined on synthetic data, in order to select the optimum parameters for field experiment planning in shallow underwater buried targets. This methodology was applied at Stomio area, in SE Crete, Greece, where a Roman villa has been discovered in the sea at a shallow water depth [4].

II. DESCRIPTION OF THE METHODOLOGY

A. Seismic Refraction Tomography

For the generation of the synthetic seismic traveltime data, the ReflexW software [5] was chosen, which provides the first arrival times of the direct and head seismic waves. For this reason, we built the model of Figure 1. Table 1 shows the parameters of the three modeled formations and the man-made targets (relics) in detail. Firstly, we compared the accuracy of the first arrivals with the analytical solutions from a two-layer horizontally stratified model, by neglecting the sea layer and the man-made targets (relics), namely using only the parameters of the Coarse and Fine Sediments. Several tests were carried out in order to select the optimum configuration of the synthetic experiment. The examined parameters were: the model size, the number of the sources and the receivers, their spacing and the cell size. We chose the optimum combinations among the ones which led to the first arrival times with the highest accuracy. Then, the model was enriched with all the man-made targets (relics), as shown in Figure 1. In addition, for SRT applicability testing, we created another model with the three targets buried 0.5m below the seabed surface and we increased the thickness (1.5m) of the coarse sediments.

Table 1: Parameters of Figure’s 1 model.

	Vp (m/s)	Vs (m/s)	density (g/cm^3)
Sea Water	1500	0	1.0
Coarse Sediments	1700	200	1.6
Fine Sediments	2000	540	2.0
Relics	2500	500	2.1

The parameters, which led to the optimum configuration of the synthetic experiment, are the following: The dimension of the model was defined (X,Z) 48x4m, the cell size 0.05m, source positions 0-48m with 0.5m spacing (roll along technique) and the maximum offset range, -10m to +10m. Two different receivers’ spacing values were tested (0.25 and 0.5m), aiming on the evaluation of discretization, both of the targets’ boundaries and layer interface. The 0.5m interval was examined since there are limitations in the available receivers and consequently, in the future application of the proposed methodology. The sea layer was not included in modeling, since it has the lowest compressional (P) wave velocity (Vp) and thus, does not contribute to the evaluation of direct and head waves first arrivals.

The data processing of the first arrivals was carried out using the Plotrefa module of SeisImager software. Two inversion parameters were tested in order to get the optimum inversion outcome. The first one was the selection of the initial model and the second, the constraints on the allowable range of the Vp velocities. The best outcome was achieved by creating an initial model with constant Vp=2000m/s and allowable Vp range 1500-2500m/s, using model smoothness along the vertical axis. In addition, two different cell sizes (0.25 and 0.5m) were tested, according to the different modelled receivers’ spacing (Fig. 2a, 2b).

Even if the true Vp values are not accurately recovered, all targets’ (relics) boundaries and the interface between coarse and fine sediments are satisfactory imaged with both 0.25 and 0.5m receivers spacing, provided that they are buried close to the seabed (Fig. 2a, 2b). The two adjacent relics are separated to each other. Spacing 0.25m resulted in a better outcome, concerning the true velocity values. The higher Vp values bellow the targets, are due to the extrapolation of the shallower ones, since ray coverage is limited to depths less than 2m.

In the case of the buried targets (Fig. 2c), the wider ones can be located. However, adjacent relics are not separated to each other, while the thinner target is no longer visible.

B. MASW

To test the effectiveness of the MASW method, full waveform synthetic seismograms were generated utilizing the E3D algorithms [6]. This module uses an elastic finite difference numerical scheme of second- and fourth-order precision in time and space, respectively, to solve the seismic wave equation. We used a compressional point source with Ricker wavelet and central frequency of 100Hz, while we kept the same layout of sources and receivers’ deployment as in SRT modeling. The sampling interval and the record length were set to 4.5μs and 200ms, respectively. The accuracy of the dispersion curves was validated using analytical solutions for both homogeneous half-space models and a horizontally layered medium, produced by excluding the relics from the model of Figure 1. In the latter case as well as in the case of seismic waves simulation for the model of Figure 1 (relics included), the sources and receivers were laid on the sea floor. Thus, Scholte surface waves were generated and traveled along the seabed.

Numerical and analytical solutions comparisons indicated that in order to resolve both the very low S-wave model velocity values (Vs=200m/s) and the thin sea and coarse sediments layers, more than 40 nodes per minimum surface wave wavelength are required, resulting to a very small grid size of 2cm.

Synthetic seismograms were processed using kriSIS algorithms [7] in Matlab environment. The MASW method inverts the dispersion curves of the surface waves to produce Vs profiles (1D Vs distribution with depth) [8]. The location of the resulted Vs profile is commonly attributed to the center of the receivers’ spread. By combining all adjacent Vs profiles, a Vs pseudo-section is created. In order to examine the effect of receivers’ spread length on the efficient mapping of targets boundaries and layer interface, three sets of forward and reverse seismic source layouts were created, using 0.25m receivers interval:

7 receivers array (1.5m length),
15 receivers array (3.5m length), and
23 receivers array (5.5m length),

where forward and reverse source layouts refer to the position of the source, located in front of the first and behind the last receiver, respectively. In these data, Scholte surface waves were analyzed and the fundamental mode from the corresponding dispersion curves was inverted, using a 10-layer initial model, smoothness constraints and fixed parameters (thickness, Vp, Vs and density) of the sea water layer.

From the above-mentioned receiver array deployments, the layout, which gave the most satisfactory results, in terms of reconstructing the targets, was the one with the 7 receivers. The longer receivers' layout provided better Vs velocity estimation of sediments layers and their corresponding interface delineation. However, the targets were not satisfactory imaged.

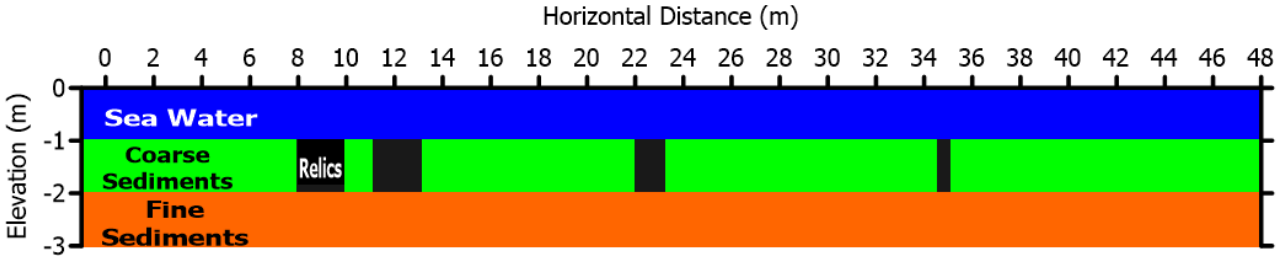

Figure 1. 2D section of the model used to create the synthetic seismic data.

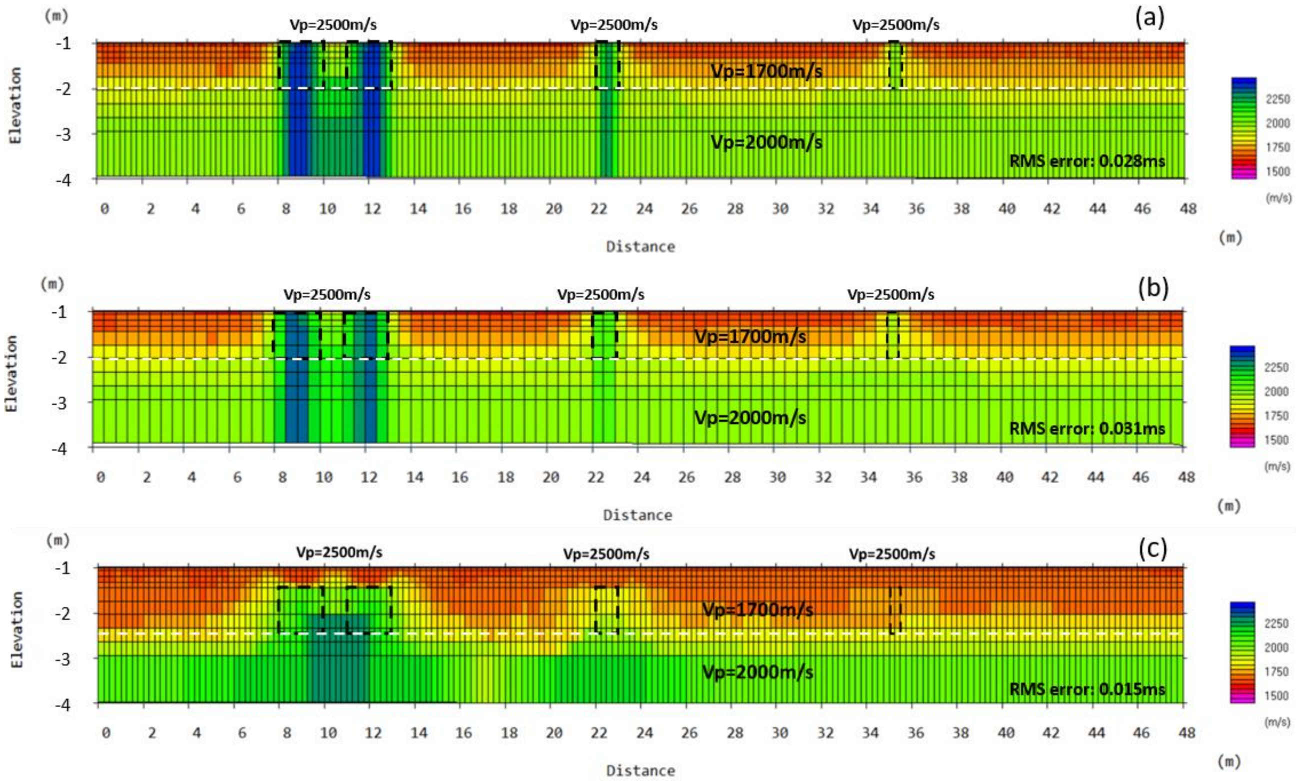

Figure 2: SRT P-wave velocity tomograms from the inversion of first arrivals deduced from the model of Figure 1. Sources and receivers were laid on the sea floor equally spaced at 0.5m and a) 0.25 m b) 0.5 m intervals, respectively. Black dashed lines indicate the boundaries of relics while the white one, the interface between coarse and fine sediments. c) The same Vp tomograms from the modified model with the buried targets using 0.25m receivers intervals.

Figures 3a and 3b show the corresponding Vs pseudo-sections deduced from the seven receivers' array, using forward and reverse source layouts, respectively. As it can be observed in Figure 3, the upper surface of the thinner (0.5m) relic (located at 35m) is not well resolved while, the wider targets appear as "dipole" velocity anomalies. Namely, each target is delineated by high Vs values at their lower left and upper right part in forward source layout (Fig. 3a), and the opposite (at upper left and lower right part) in reverse source layout (Fig. 3b). This can be justified if we consider that the nearest to the source receivers, carry information from shorter surface wave wavelengths and hence from shallower formations, while the furthest to the source receivers, carry information from longer surface wave wavelengths and hence form the deeper ones.

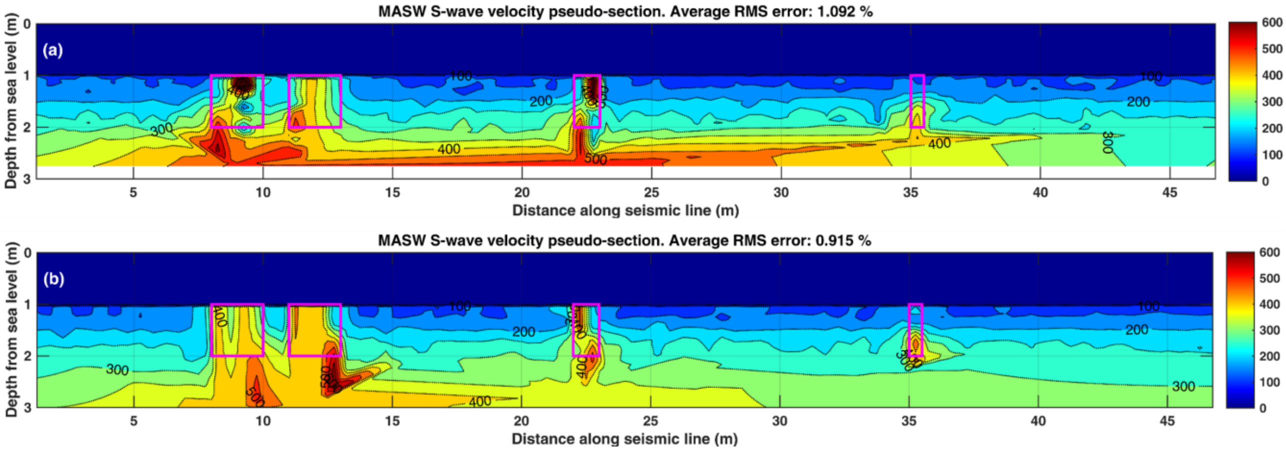

Figure 3: MASW S-wave velocity pseudo-sections deduced from synthetic data with (a) forward and (b) reverse source layouts. The magenta rectangles delineate the positions of the relics. The color scale represents the Shear wave velocity (Vs).

III. THE CASE STUDY FROM STOMIO

The methodology described so far was applied at Stomio area, in SE Crete, Greece, located 6km west from the city of Ierapetra (Fig. 4). This site is of particular archaeological interest, since a Roman villa has been discovered at a shallow water depth. The main goal of this survey was to validate the proposed methodology with real data, over an area where submerged building walls were visually detected at the bottom of the sea. For the seismic data acquisition, we used a 12-channel hydrophone streamer (MP25SW of Geospace) with sensors at 0.5m intervals (5.5m receiver length), a 12-channel GEODE (Geometrics) seismograph and a 1kg hammer with a metallic plate as a source. A piezoelectric device was mounted on the hammer to trigger the seismograph. The sampling interval and the record length was set to 31.25μs and 100ms, respectively.

Two seismic lines were surveyed at the investigated area near the Roman villa (Fig. 4). Along each line, the hydrophone streamer was submerged on the bottom of the sea and rolled 5 times with 1.5m overlap, leading to a total length of receivers' spread equal to 23.5m. For each hydrophone spread 13 shot positions were selected: 11 positions between the receivers and 2 outshots with nearest offset of 0.25m. At each source position, the water thickness from the sea surface to the sea bottom was also measured with a measuring tape. Along Line 1, the remains of three stone structures (walls) were visually detected at the bottom of the sea at: 7.1-7.8m, 9.8-10.7m and 18.2-18.6m.

Regarding the data processing of Line 1, we were unable to apply the seismic refraction tomography method, since we faced problems recording accurate first arrival times, due to slight (<2ms) but crucial (e.g. the anticipated direct waves at the nearest offset is < 0.2ms) delays in triggering with the piezoelectric device.

Regarding the processing of these data with MASW method, as demonstrated from the processing of the synthetic ones and aiming to enhance the lateral resolution in the mapping of wall structures, a shorter (than 5.5m) array of four hydrophones (with 1.5m length) was utilized, both in forward and reverse source layouts. Figures 5a and 5b show the corresponding Vs pseudo-sections deduced from the inversion of the four-receivers' array of Line 1 data, using forward and reverse source layouts, respectively. The magenta frames delineate the positions of the visible walls. Their height was arbitrary extended to the maximum depth of investigation, indicated by the white dashed line with circles at the bottom of the sections. Deeper than this line S-wave velocity values were created by extrapolation and should not be taken into account.

Figure 5, displays the wider wall, visible at 9.8-10.7m along the Line 1, which is successfully imaged. The "dipole" velocity anomaly, described for synthetic data, applies at the shallower part (from sea bottom to a depth of 1.7m) of this target. In addition, the wall, visible at 18.2-18.6m, is successfully reconstructed with the typical "dipole" velocity anomalies (lower left and upper right and the opposite for forward and reverse source deployment). The width of this structure, according to the Vs section, is estimated to be 1m (from 17.75 to 18.75m) or more. The dimensions of wall, observed at 7.1-7.9m, is not well resolved, especially in the reverse section. However, from both sections, it is relatively easy to locate the structure at this position.

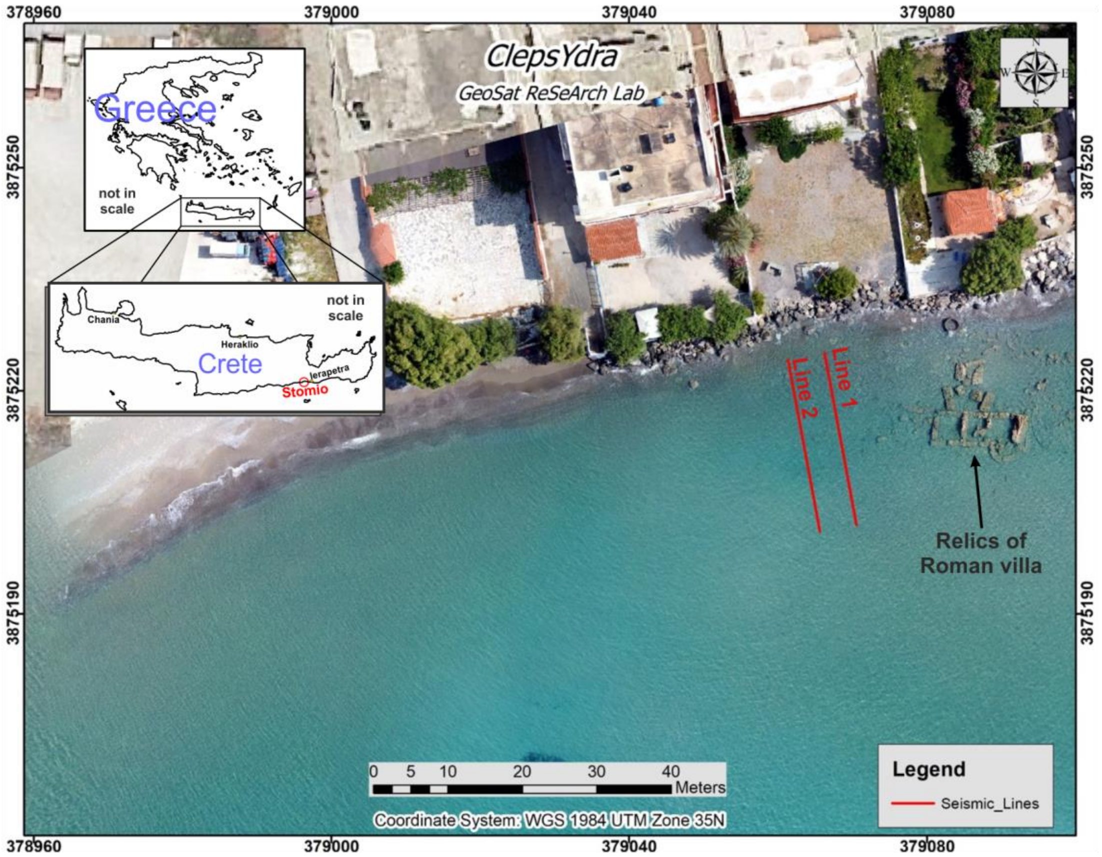

Figure 4: Aerial photo of the investigated area. Seismic lines were surveyd along Lines 1 and 2 near the relics of a submerged Roman villa.

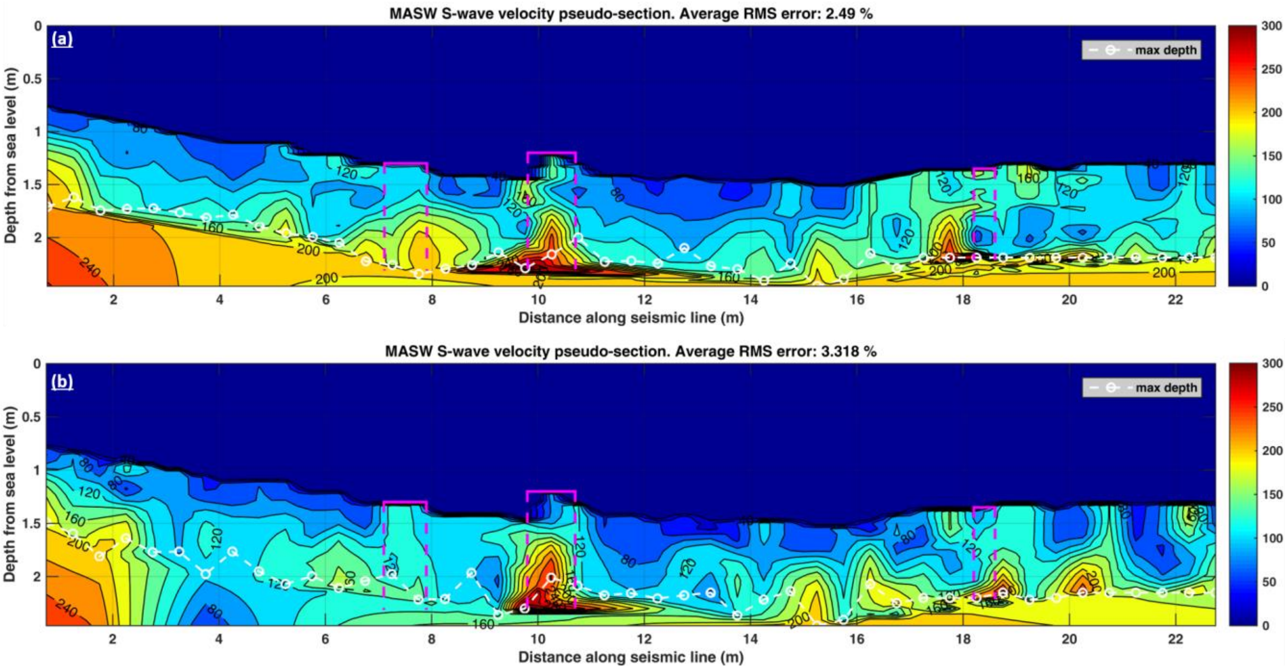

Figure 5: MASW S-wave velocity pseudo-sections deduced from the real data of Line 1 with (a) forward and (b) reverse source layouts. The magenta frames delineate the positions of the relics while the dotted white line with circles the max depth of investigation. The color scale represents the Shear wave velocity (Vs).

IV. CONCLUSIONS

The case of shallow buried targets in a shallow sea water environment is mainly examined in this study. The modeling results, as well as the results from the application of MASW method in real data, are quite promising for mapping architectural relics in shallow aquatic environments.

The seismic modeling approach contributed to establish the optimum processing steps of both the SRT and MASW methods. In SRT method, the selection of a homogeneous half-space as initial model (with Vp=2000m/s) and the use of relatively narrow velocity range (Vp=1500-2500m/s) constraints provided the best tomograms in the terms of the reconstruction of the submerged relics. In addition, although the receiver spacing of 0.25m provided the most accurate velocity representation of the model, the 0.5m spacing (which is a feasible field acquisition parameter) gave acceptable results, concerning the location of the targets. However, we must first resolve the technical difficulties in real data acquisition, which concern the delays in recording, before we proceed with the processing of the SRT data.

In MASW method, we conclude that shorter receiver array length gave better location results in terms of very shallow targets, provided that the multichannel acquisition is not violated. For longer receivers' deployments, the results were considered insufficient in delineation of the buried targets. However, it seems that there is a correlation between the above-mentioned results, since the "dipole" velocity anomalies, observed at the positions of targets, are mirrored in forward and reverse source layouts. These observations were verified, as well, from the real data results.

Taking all the above mentioned into consideration, synthetic data creation and processing provide a step closer to the use of seismic methods in a shallow marine environment, in order to image targets of archaeological interest. The outcomes of modeling were verified during the next challenging step, which was the implementation and the corresponding data processing of the MASW method in a case study with visually observed targets in a shallow aquatic environment.

ACKNOWLEDGEMENTS

This work received funding by the research project ClepsYdra: Translating submerged and buried cultural heritage from shallow water to digital environment with geoinformatics" that is supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "2nd Call for H.F.R.I. Research Projects to support Faculty Members & Researchers" (Project Number: 3339).

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