Assessment of near-surface geophysical measurements for geotechnical purposes at the area of Goudi (Athens, Greece)

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Summary

The present study aims to present the results of a near-surface geophysical investigation carried out at a construction site in the area of Goudi (Athens) along with its contribution to the determination of the geotechnical characteristics. For this purpose, the Ground Penetrating Radar (GPR), Electrical Resistivity Tomography (ERT), Seismic Refraction Tomography (SRT) and Multichannel Analysis of Surface Waves (MASW) techniques were implemented in the area. The cores of three geotechnical boreholes existing in the area have also been taken into account. The application of the GPR and ERT techniques did not reached a satisfactory investigation depth, however the existence of a possible mechanically degraded zone have been adumbrated at the south part of the excavation area. Through the application of the SRT and MASW techniques, the seismic waves velocities of the investigated lithological formations were calculated and the subsurface structure of the study area was outlined. Additionally, lateral variations in the P-wave seismic velocities, especially in the first investigated seismic layer, provided further evidence for the existence of mechanically unstable zones, which necessitate a more detailed investigation. Finally, from the laboratory determination of the formations' densities and their seismic wave velocities, their elastic moduli and geotechnical parameters have been calculated.

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Introduction

Nowadays, near-surface geophysical investigation has received great attention in geotechnical site characterization purposes. Through the implementation of geophysical techniques, such as Ground Penetrating Radar (GPR), Electrical Resistivity Tomography (ERT), Seismic Refraction Tomography (SRT) and Multichannel Analysis of Surface Waves (MASW), the characterization of the near-surface materials in relation to their geotechnical conditions can be assessed (Alhussein and Nouran, 2022). In this case, the subsurface structure and geotechnical characteristics of the under construction building area at the Dental School of National and Kapodistrian University of Athens has been studied, by applying the aforementioned geophysical techniques. The first geophysical technique applied was the GPR, which is a fast, cost-effective technique that provides a first look into the internal structure of the subsurface materials. Subsequently, the high resolution ERT technique was performed as it is very sensitive to lateral variations of the formation's resistivity. For the determination of the compressional (P) and shear (S) wave seismic velocities, of the investigated lithological formations, the SRT and MASW techniques were applied respectively. The calculated seismic velocities in conjunction with the calculated densities of the formations resulted to the calculation of their elastic moduli and several geotechnical parameters such as the concentration index (Ci), material index (Mi), stress ratio (Si) and density gradient (Di).

Methodology

At the study area three existing (3) geotechnical boreholes, have been taken into account for the calibration and interpretation of the geophysical techniques, providing useful information about the subsurface structure. Based on their drilling cores, the study area consists of 8.5m fine to coarse grain anthropogenic materials overlying the weathering layer of the Athens schist formation, which was found until the depth of 11.20, 14.50 and 13.00m at boreholes B6, B7 and B8 correspondingly. At greater depths, the compact Athens schist formation was found, which is practically a complex mélange without internal geometry, comprised of unmetamorphic clastic sediments, such as sandstones, pelites, clays, sandstone marls, greywackes, tuffs and argillic schists (Papanikolaou *et al*., 2002). During the data acquisition period, the water table level was measured at 10m depth. Furthermore, density laboratory measurements were also performed, on borehole samples of the lithological formations.

In the context of the geophysical survey, seventy-three (73) GPR sections, on a 1x1m grid and total length of 1457m were implemented, constrained to the under construction building area. Moreover, four (4) ERT sections and three (3) SRT sections, along with three (3) 1D MASW measurements, were also performed, taking advantage of the maximum possible length in the study area. In Figure 1, the acquisition layout of each geophysical technique is illustrated, along with the locations of the three (3) boreholes (B6, B7 & B8) that had been drilled in the area. All the geophysical measurements were topographically corrected based on GNSS measurements with the RTK-NTRIP technique.

Regarding the GPR technique, the data acquisition was carried out using a 100MHz bistatic shielded antenna provided by *Sensors & Software*. Each GPR section vertical trace was composed by 135 samples within a time window of 108ns. A typical processing flow was employed, using the *EKKO_Project* software, by applying the Dewow, Background removal, Bandpass filter, SEC2 Gain and migration. All the acquired GPR data have been subjected to a 3D process, for the generation of volume/depth slices. The illustrated slice (Fig. 2) corresponds to a depth range of 0.8 to 1.0m, where at the South part, high intensity reflection areas can be observed, probably occurred by a lateral variation in the internal structure of the investigated lithological formation.

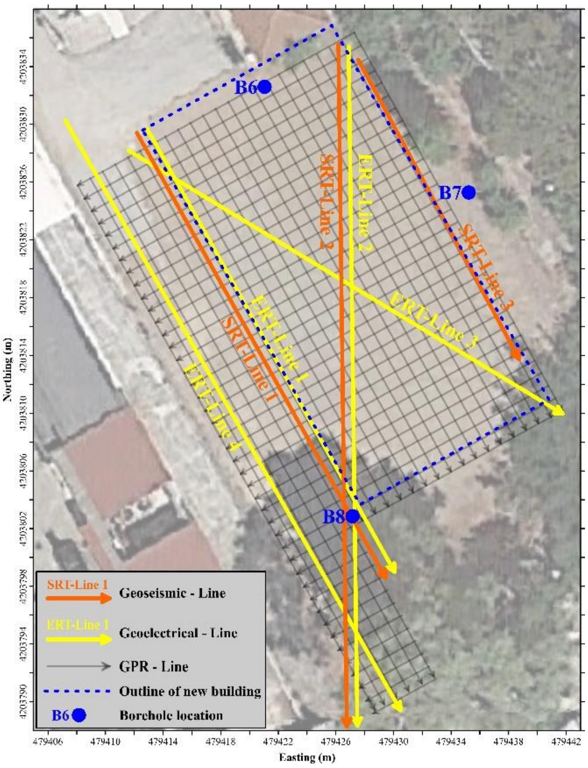

Figure 1 Acquisition layout of the geophysical techniques applied in the study area

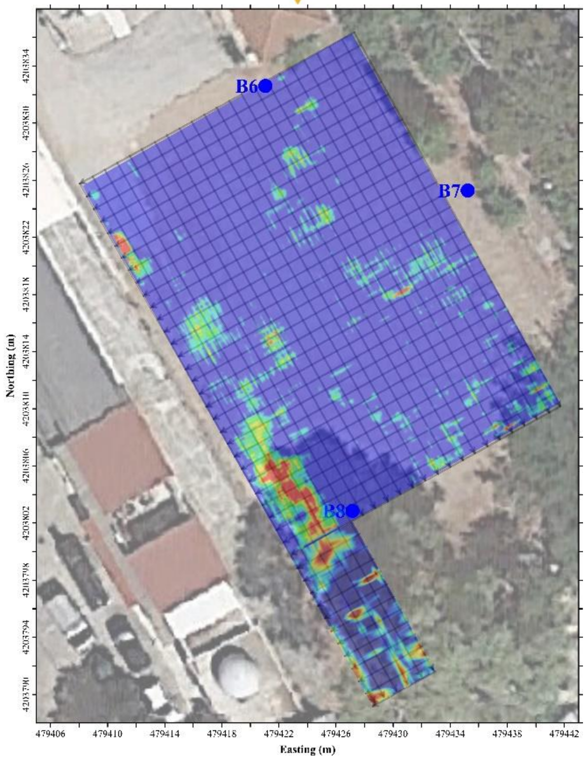

Figure 2 GPR volume/depth slice for the depth range of 0.8 to 1.0m

The geoelectrical data were collected using 48 electrodes, connected to the *IRIS Syscal Pro* unit, with a variable spacing of 0.75m for the ERT lines 1 & 3 and 1.0m for the ERT lines 2 & 4. The Dipole-Dipole electrode array was selected, due to its sensitivity to lateral resistivity variations. The resistivity data were inverted using a smoothing-constrained least-squares inversion approach which is incorporated by the *Res2Dinv* software by *Geotomo* (Loke, 2020). The final inverted resistivity tomograms were produced, achieving an RMS error lower than 2.0% for all the ERT lines. In Figure 3, the processing result of the ERT line 2 is presented, where relatively low resistivity values are investigated in general (60-200 Ohm.m). At the beginning of the section (up to 13m) and between 23-34m the resistivity values are relatively higher (200-600 Ohm.m) revealing an inhomogeneous subsurface. Additionally, a resistant anomaly (>600 Ohm.m) is presented, at almost 1.5m depth and profile distance 37-42m.

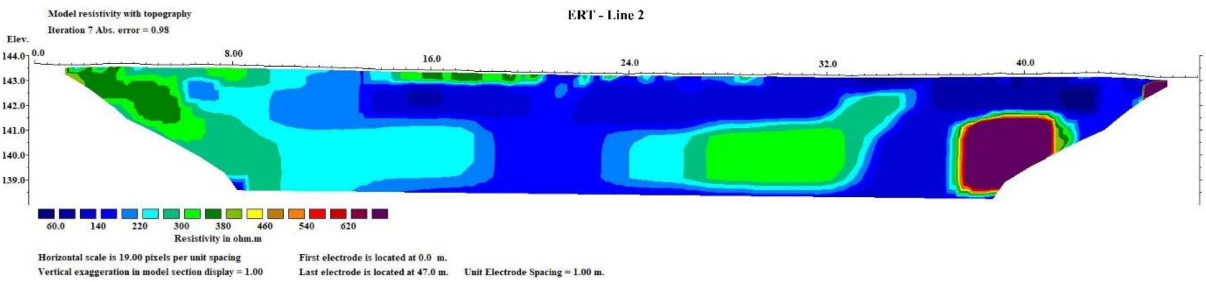

***Figure 3** Electrical resistivity tomography section at the ERT line 2 location*

Field measurements of seismic data were acquired using a 48-channel *Geometrics StrataView* seismograph, with a sampling interval of 0.250ms and a total record length of 512ms. Along each seismic line, a 6.5kg sledgehammer was used for the generation of the seismic waves at 13 shot locations, with 3 to 5 stacks in order to increase the S/N ratio. Two (2) of the shot locations were performed at a near-offset distance of 4m, from the first and last geophones, for the 1D MASW processing. The remaining eleven (11) shot locations were used for the SRT processing, including two

(2) outshots at 10m offset and nine (9) shots performed in between the spread length. The propagated waves were detected along the surface by 48 vertical geophones with a natural frequency of 4.5Hz. The geophone spacing was variable with 0.5, 0.75 and 1.0m for the SRT lines 1, 3 and 2 correspondingly.

Seismic data processing was carried out using the *Geogiga Seismic Pro 10* software. Regarding the SRT technique, the *DW Tomo* module was used for first break arrival picking and 2D inversion analysis. Based on the borehole results, and by employing a simple intercept-time method at the generated travel-time curves, a three-layer gradient initial model was generated for all the SRT lines, transitioning from 600 m/s at the surface to 1350 m/s at 5.5m depth and finally to 2680 m/s at 12.2m depth, with a maximum investigation depth of 15m. The model's grid spacing was 0.5m and 0.25m for the horizontal and vertical directions respectively. The software uses the "shortest path" raytracing method (Moser, 1991) in order to calculate the synthetic travel-times and raypaths and a smoothing constrained regularized inversion approach to iteratively update the velocity model. For the inversion step, 5m horizontal and 1.25m vertical smoothing lengths were selected, while a total number of 30 iterations was chosen in order to achieve an acceptable minimum misfit error between the observed and synthetic travel-times. A representative seismic tomography section for the study area, corresponding to the SRT line 2 is shown in Figure 4. An upper seismic layer can be observed with an average P-wave velocity of 700m/s and a maximum thickness of 8m at the central part of the section, which decreases towards the beginning and end to about 6m. Underlying, a second seismic layer is present with an average velocity of 1500 m/s and thickness ranging from 2 to 5m. Finally, a third seismic layer can be located at depths greater than 8m, at the beginning of the section, and 13m towards the middle, with Vp > 1900 m/s.

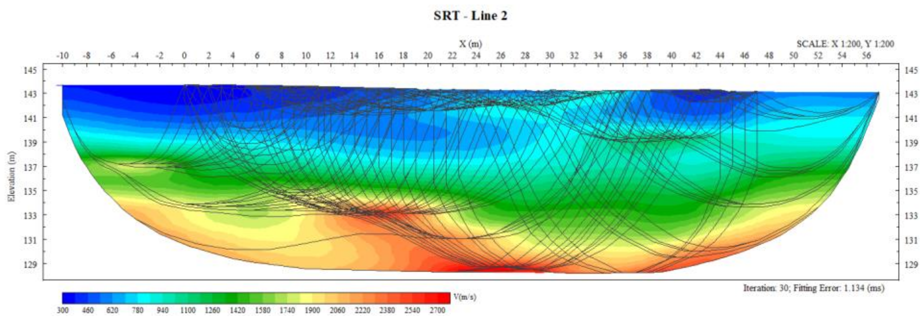

Figure 4 *Seismic refraction tomography section at the SRT line 2 location*

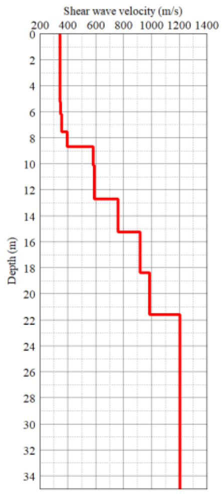

Figure 5 *1-D shear wave velocity model, derived from the MASW technique, at the SRT line 2 location*

The acquired datasets for the 1D MASW technique were processed using the *Surface* module of *Geogiga Seismic Pro 10* software. Each seismic record was processed individually by applying a 2D Fourier transform, in order to generate the dispersion image. In the F-V domain, the maximum energy amplitude of the surface waves was peaked at a frequency range of 5-40 Hz, composing the dispersion curves, which correlate each frequency value with a specific phase velocity. The initial model required for the inversion, was created automatically by generating a multilayered model. The model's first layer thickness was determined by the highest frequency peak, while the thickness of the consecutive layers was determined using the following formula:

$$H_{i+1} = H_i R$$

Where H_i the thickness of the i^{th} layer and R a common ratio with a value of 1.2. The maximum model's depth was specified by the longest recorded wavelength. Subsequently, the dispersion curves were inverted using the genetic algorithm inversion approach. In Figure 5 the result of the MASW technique at the SRT line 2 location is illustrated, which corresponds to the midpoint of the active spread. Until the depth of 8.5m a seismic layer with a shear wave velocity of 330 m/s can be observed. Subsequently, there is a continuous increase in the shear wave velocity from 330 to 1000 m/s, up to the depth of 21.5m. Below this depth, the velocity stabilizes at around 1200 m/s.

Conclusions

The combined application of the geophysical techniques proved to be very effective, providing useful information about the structure and geotechnical properties of the subsurface lithological formations. The GPR and ERT techniques had the lowest investigation depth; the former due to the high clay content in the anthropogenic materials and the latter due to the restricted available area for the technique application. However, both techniques managed to delineate a subsurface area characterized by high reflectivity of the electromagnetic waves and high resistivity values (>600 Ohm.m). This zone could be interpreted as a lateral variation of the anthropogenic materials layer, probably consisting of unconsolidated, high porosity, unsaturated materials. On the other hand, seismic measurements have reached greater investigation depths, up to 34m, making possible to investigate all three lithological formations that are present in the study area and determine their seismic velocities. Through the implementation of the SRT technique, a subsurface velocity model was obtained revealing three seismic layers (Fig.4), corresponding to the lithological formations found by the boreholes. Moreover, lateral variations in the P-wave seismic velocities (Fig.4), especially in the first investigated seismic layer, enhance the possibility of lithological variations existence within the anthropogenic materials formation. More specifically, the zone where the aforementioned GPR and ERT geophysical anomalies are located, is characterized by a degradation in the P-wave seismic velocities. Finally, the elastic moduli and geotechnical parameters of the investigated lithological formations have been calculated (Table 1), after the laboratory determination of their densities.

Table 1: *Geophysical and geotechnical characteristics of the lithological formations*

Lithological formation	Vp (m/s)	Vs (m/s)	ρ (g/cm^3)	ν	E (GPa)	G (GPa)	K (GPa)	Ci	Di	Mi	Si
Anthropogenic materials	700	330	1.70	0.36	0.50	0.19	0.69	3.80	-0.47	-0.43	0.56
Weathering layer of Athens schist	1500	750	2.60	0.33	2.55	0.96	4.75	4.00	-0.50	-0.33	0.50
Athens schist	2300	1200	2.67	0.31	6.43	2.45	11.24	4.20	-0.52	-0.25	0.46

Acknowledgements

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