Non-invasive depth estimation of Delos quarries

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Abstract
A lightweight geophysical survey method was used to estimate quarry filling layer thickness based on EMI and DCP data.

Keywords
archaeological prospection; Delos; dynamic cone penetrometer; EMI; quarry thickness estimation

Introduction

The island of Delos is an important archaeological site in Greece, despite it being one of the smallest islands in the Cyclades. Mythologically, it is said to be the birthplace of Apollo and Artemis and enjoyed high religious prestige and aura. Its famous sanctuary, combined with its port and its importance in trade in the Hellenistic era, led to the development of the island and its urban expansion. As a result, from the third millennium BC until the sixth century AD, hundreds of public and private buildings were erected in Delos, constructed using both local and imported materials from the surrounding islands or mainland Greece. In 2018, the multidisciplinary research project GAD (Geology and Architecture at Delos) was launched and aims to study all the stages in the use of stone in the monuments of Delos, from its extraction in a quarry to its implementation. It is led by J.-Ch. Moretti and funded by the French National Research Agency. Estimating the total volume of rock extracted on the island is a key part of this research project and the main objective of the work presented in this paper.

Twenty open pit quarries which exploited gneiss and granite have been identified in the northern part of the island. These quarries are now partly filled with a mixture of blocks of rocks and fine sediments of an undetermined thickness. The determination of this thickness is crucial for the estimation of the total volume of extracted rock. Estimating the thickness through direct digging was not possible within the framework of the project. During spring 2022, geophysical and geotechnical methods have therefore been used in this initial investigative study of the quarries on the northern part of the island. This project took place in the framework of the work of the French School at Athens, in partnership with the Ephorate of Antiquities of Cyclades.

The underlying hypothesis for this paper is that there are significant mechanical and electrical contrasts between the filling layer of the quarries and the geological substratum. As it is at least partly composed of fine and salty sediments, the filling layer is expected to be more conductive and less compact than the bedrock. The objectives were (1) to confirm the existence of this contrast and propose a simple and easy-to-implement methodology that could then be applied to all the quarries and (2) to get a first estimation of the filling layer thickness on a few sample quarries.

As this was an initial study, light acquisition equipment was used to perform electrical soundings (ES), frequency-domain electromagnetic induction (EMI) measurements and dynamic cone penetrometer (DCP) soundings.

Materials and methods

The lightweight dynamic cone penetrometer used in this study (the PANDA® by Sol Solutions, Fig. 1) characterizes the mechanical resistance of the ground by driving a rod

Fig. 1: Implementation of DCP sounding (top left), EMI mapping (top right) and example of quarry configuration (bottom) in Delos.

into the ground. The simultaneous measurement of the variable strike energy and the penetration depth of the rod after each blow allows us to calculate the ground resistance at the rod tip and to discriminate ground layers based on their mechanical properties. Due to the limited number of rod segments available, the maximum depth the DCP could reach was approximately 2.25 m. The rod can only pass through relatively soft media and would not penetrate the substratum. A stoppage is however not a definitive indication that the rod reached the bottom of the quarry as it could have encountered a block of rock. Nevertheless, these soundings give an important indication of the minimum thickness of the filling layer as the substratum cannot be above the penetration limit of the rod.

Electrical soundings were performed using a versatile and lightweight resistivity meter (the 4point light 10W by Lippmann Geophysikalischen Messgeräten) to provide a 1-D model of the ground electrical resistivity with depth. A simple Wenner configuration was used and the electrode spacing was limited to a maximum of 15 m due to the available cable length.

As EMI is also sensitive to the electrical properties of the ground and is able to map soil conductivity with different depths of investigation, it was used in order to map the filling layer when possible and also as a complementary dataset to the ES. EMI soundings were attempted where mapping was not possible, using measurement at three different heights above the ground. Although the filling layer thickness has yet to be determined, it could

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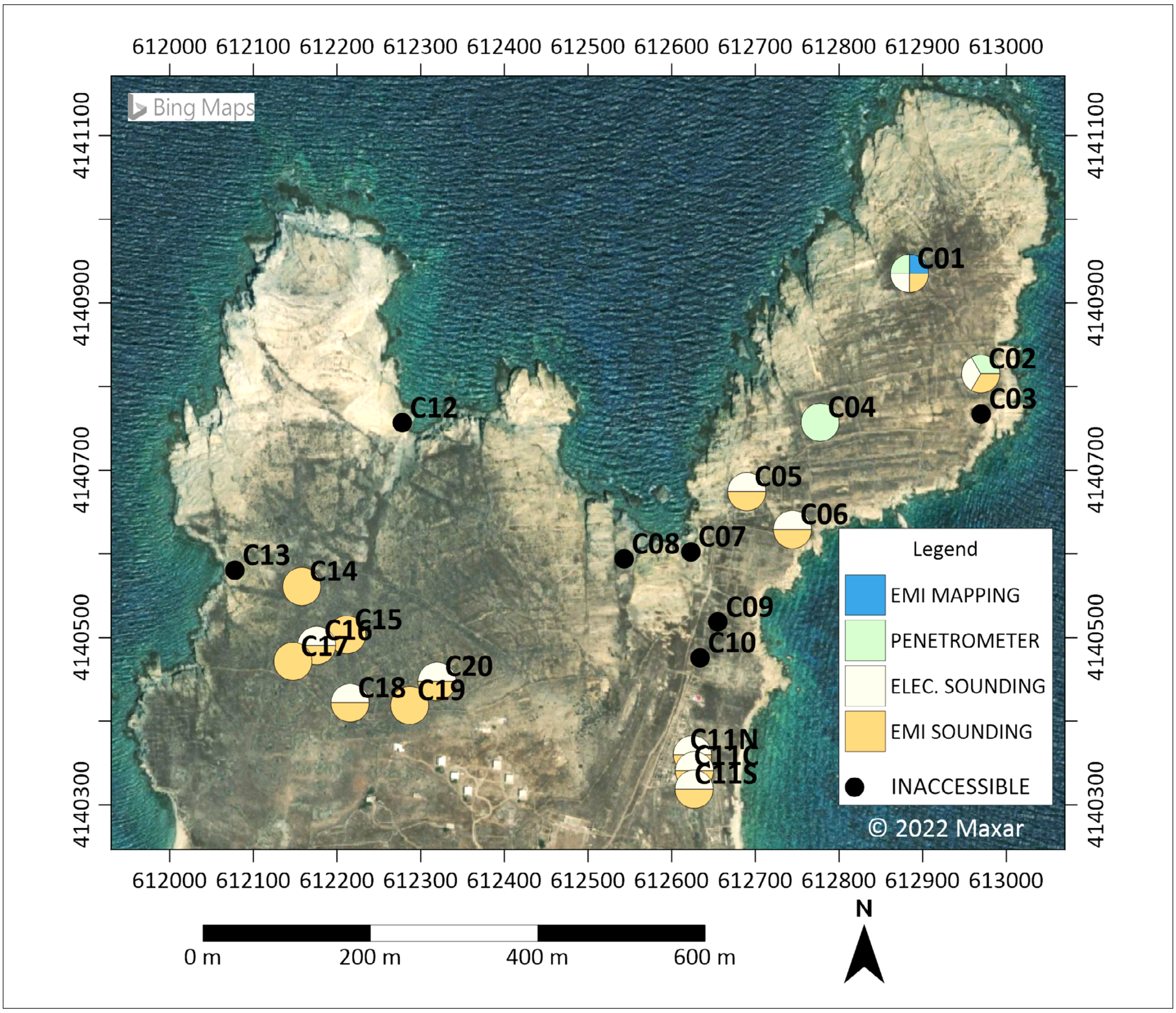

Fig. 2: Implemented methods on each quarry of the north of Delos.

potentially be several meters thick. A CMD-Explorer (by GF Instruments, Fig. 1) was therefore used as it offers at least three different penetration depths ranging from one to approximately six meters.

As the quarries' configuration and geometry are very different, it was not possible to implement all geophysical methods in all of them. Some were filled with water, blocks of rocks or vegetation and were therefore inaccessible. In order to have a general overview of the northern part of the island, ES and EMI soundings were acquired in all of the accessible quarries. In addition, quarry C01 was chosen as a test area for more detailed research because of its favourable geometry (Fig. 2). We were able to use all the available methods for soundings (ES, EMI, DCP) and establish a full EMI map for this quarry.

Results and discussion

The ES acquired on the different quarries all showed a very conductive filling layer (from 35 Ωm to less than 10 Ωm), confirming the existence of contrasting electrical properties. However, because this layer is so conductive, the estimation of its thickness would require a long electrode array as well as an important injection power. Because of the limited extension of most quarries, the resistive underlying substratum could not be reached, and the thickness of the filling layer was not estimated using this method.

The attempted EMI soundings did not prove to be satisfactory: only the middle height measurement (~1 m) seems to be sufficiently reliable to be inverted. Including

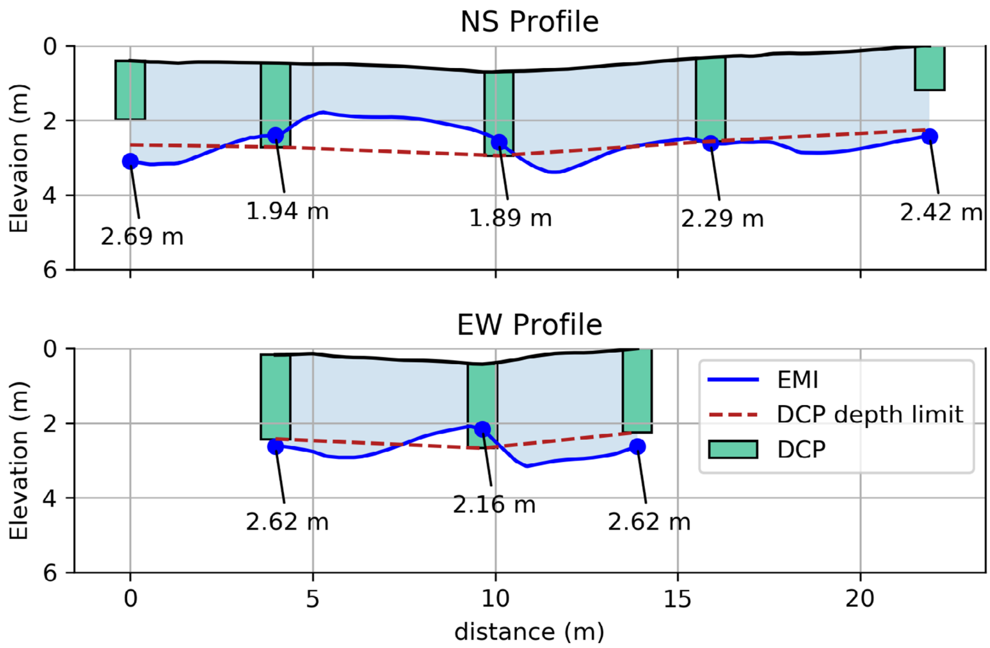

Fig. 3: Comparison of DCP and EMI results on the north-south and east-west profiles of the quarry C01 of Delos.

the other heights only resulted in a less reliable estimation of the sub-soil thickness. The EMI soundings were therefore disregarded. However, the EMI mapping in both HCP and VCP configurations (Rejiba et al. 2018), as implemented in quarry C01, resulted in a very promising thickness estimation.

On C01 (Fig. 2), two perpendicular ES were acquired in the quarry's center. DCP and EMI soundings were acquired along two profiles oriented north-south and east-west and a full EMI map of the quarry was established. The DCP located in the center of the quarry all reached the limit of 2.25 m (Fig. 3), indicating a minimum depth of the quarry. The profiles extracted from the EMI inverted map show comparable results with a maximum estimated thickness close to 2.80 m.

Conclusion

Up to four lightweight geophysical methods were implemented on the north of the island of Delos to try to estimate the quarries' filling layer thickness. Due to the variety of quarry configurations, it was only possible to implement all the geophysical investigation techniques we intended to use on one of the quarries. Electrical and electromagnetic soundings turned out to be mainly unsuitable for the site but confirmed the existence of contrasting electrical properties between the filling layer and the substratum.

The DCP soundings showed convincing results, although the depth of investigation had to be limited to 2.25 m. They provided a minimum thickness of the filling layer in the quarries.

EMI mapping led to thickness estimates broadly in agreement with the DCP results, although this thickness appears to be underestimated at the center of the quarry.

For future investigations, the use of additional rod segments and of a mechanical rod extractor would make it possible to remove the rods more easily from the ground and therefore to exceed the limit of 2.25 m of rod penetration set for this study. Furthermore, at the widest electrodes spacing, the signal-to-noise ratio was often poor and the use of a more powerful resistivity meter would make it possible to implement ERT profiles crossing the quarries with a better chance of reaching the substratum. Finally, other methods, not tested during this first study because they were too heavy to transport and implement, could be considered for future acquisitions in selected quarries, such as the seismic method as it is sensitive to mechanical contrasts.

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