Engineering Geology and Soil Mechanics: The Need to Develop Educational Material that Captures their Relationship

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ABSTRACT: The motivation for writing this paper was the scarcity in the geotechnical engineering literature of material that can be used in instruction to demonstrate how the knowledge of the genesis of the soil profile can be useful to geotechnical engineering. The lack of a dedicated map of soil deposits in Greece intensified the urgency to address this gap in the literature. The approach followed towards filling this gap was to start a campaign for the need to create such a map for educational purposes, to compile some guidelines that can complement information from boreholes, and to contrast two case studies with inhomogeneous vs homogeneous soil profiles.

Keywords: Soils, Engineering Geology, Soil Mechanics

1 Introduction

The investigation of the relationship between Engineering Geology and Soil Mechanics in this paper aims to highlight the geological knowledge that has decision value to geotechnical engineers and can be meaningful to soil mechanics students. Karl Terzaghi had an early fascination with the natural sciences and took several geology courses as a mechanical engineering student, before his inquisitive and restless mind finally settled to Civil Engineering where he could work in Engineering Geology, an involvement that turned out to be life-long and deep (Goodman, 1999). Perhaps, then, it is surprising that Terzaghi never completed his book on Engineering Geology, especially considering that he taught a course on the subject at Harvard, from which we have only class notes taken by two of his students in the 1950s (Goodman, 2003). Terzaghi had co-authored a book in German with the title Ingenieurgeologie (Redlich et al., 1929), but, according to Goodman (2003), “his contributions in that volume were mainly on the engineering side”. Contents of more recent engineering geology books (e.g. Goodman, 1993) and engineering geology courses in civil engineering curricula give the impression that the medium of interest is solely or primarily rock.

But when Karl Terzaghi (1961a) writes about the importance of Engineering Geology, he discusses first Soil Mechanics, or “Earthwork Engineering”, separately from Rock Engineering. As a general guideline for Earthwork Engineering, Terzaghi states that if the subsoil exploration reveals inhomogeneity, then the geological characteristics will give an indication of the uncertainties to be expected. Similar guidelines about what to expect are rarely found in the literature. In a related article, Terzaghi (1961b) gives an example by contrasting varved clays deposited in still water, which will be homogeneous in the horizontal direction, with clays in drowned valley deposits, which are likely to vary over short distances both in the horizontal and the vertical direction due to variations in the currents depositing them. This example by Terzaghi perhaps implies that it is more manageable to demonstrate the value of knowledge of the geological processes by contrasting cases, an approach which was adopted herein. Similar examples of contrasting behavior are also rarely found in the literature: one exception known to the authors is the example concerning slope characterization in river valleys by Abramson et al. (2002: p.236) who recommend closer boring spacing perpendicular to the valley axis compared to the spacing along the valley line.

The fact that such examples are continent-, country-, region- and location-specific shaped the scope of this paper, which includes: (1) compiling guidelines and presenting examples from regions with extensive areas of soil deposits and (2) focusing on Greece with the dual aim (2i) to produce a first map of Quaternary deposits, specifically its Holocene subset for a start and, with such a map as a frame, (2ii) to assemble existing information on major occurrences of recent soil deposits and identify information gaps to be addressed piecemeal by future work. Holocene deposits vary in thickness from a few meters to a couple of tenths of meters and are often the foundation material for engineering works such as bridges and buildings.

2 Soil deposit maps and engineering behavior

We hypothesize that the availability of country-wide soil deposit maps will encourage the study of their geological characteristics with the goal of offering a first estimate of their engineering behavior. At the very least, the availability of these maps will provide a place to start when building a soil profile and help anticipate soil type (e.g. sand, clay), soil deposit depth and degree of inhomogeneity.

The British Geological Survey (BGS) has produced a Quaternary map of the United Kingdom with a classification of deposits based on soil type, with some information on their depositional environment (BGS, 1977). More recently, BGS (Lawley and Garcia-Bajo, 2010) has compiled data suitable for producing a map of the location of the Quaternary-age surficial deposits across Great Britain (the paper includes only an indicative very small size, low-resolution such map), and created a model for their depth (which ranges from 1 m to 160 m, typically between 1 m and 20 m). In the Netherlands, similar borehole data for geological units dating back to the Cretaceous were incorporated in a model providing general information on the depositional environment (e.g. fluvial, glacial), the main type and the thickness of these units (Gunnink et al., 2013). All the Holocene deposits are represented as a single geological unit and the paper includes a map showing their areal extent. The authors have not located articles describing examples of how the maps that can be produced with these models either influenced selection of borehole locations or enriched the information provided by the borings.

It should be noted that herein we are interested in general-coverage maps, not in maps with soils of unusual behavior such as the quick clay deposits in Norway. (Naturally, the availability of geological maps in different countries is related to their specific needs.) Abramson et al. (2002) provide such a general-coverage map in their Figure 2.1, which shows a distribution of soils in the United States, distinguishing among alluvial, residual, loessial and glacial soils, referencing as a source the 1971 edition of the NAVFAC Design Manual 7. However, the 1986 edition of the NAVFAC Design Manual 7 (NAVFAC, 1986) does not include such a figure.

The same case study (an underground car park in London) discussed independently by Burland (2012) and de Freitas (2012) confirms the importance of a detailed knowledge of the soil profile– specifically, in this case, the existence of high permeability inclusions in clay. However, the two authors do not say anything about some geological characteristic that provided information about these higher permeability inclusions. In other words, from their discussion it is not apparent that certain geological characteristic(s) alerted them to the presence of these inclusions.

This is a good counter-example for what we are *not* after: the question being asked is not “what are the geological processes that resulted in the formation of these high permeability inclusions”? Instead we ask “what is the added value provided by the knowledge of the geological processes for the prediction of the engineering behavior of the soil formation?” Or, stated differently, “how does knowledge of the geological history of soils complement the information from soil borings?” Following Terzaghi’s advice, the answers offered focus on the expected heterogeneity of the soil deposits and its implications for geotechnical characterization.

3 Soil deposits in Greece

Greece is a mountainous country, to a percentage of 80% according to the criteria used by the European Union to define mountainous regions (Nordregio, 2004). Considering their frequency, there are clear incentives for the study of rock formations. On the positive side, the relative scarcity of soil deposits in Greece (compared to other countries) makes more manageable the undertaking of studying at least their major occurrences.

3.1 Map of soil deposits

The main Neogene and Quaternary sedimentary basins of Greece are sketched in Figure 1a (map re-drawn from original map by Mountrakis, 2010). Nine main basins are identified herein: 1) the Evros river basin, 2) the Nestos river basin, 3) the Strymonas river basin, 4) the Aliakmon, Loudias, Axios, Gallikos rivers-Thessaloniki basin, 5) the Florina-Vegoritis-Ptolemais basins, 6) the Larissa-Karditsa basins, 7) the Argos-Korinthos-Xylokastro basins, 8) the Pyrgos-Kyllini basins, and 9) the Iraklion basin in the island of Crete. The bulk of soil deposits are located in the basins shown in Figure 1a and correspond roughly to the areas depicted with green color in the slope map in Figure 1b. A crude estimate of the age distribution of soil deposits in Greece is that about 80% of all soils are Quaternary, of which 70% are Holocene.

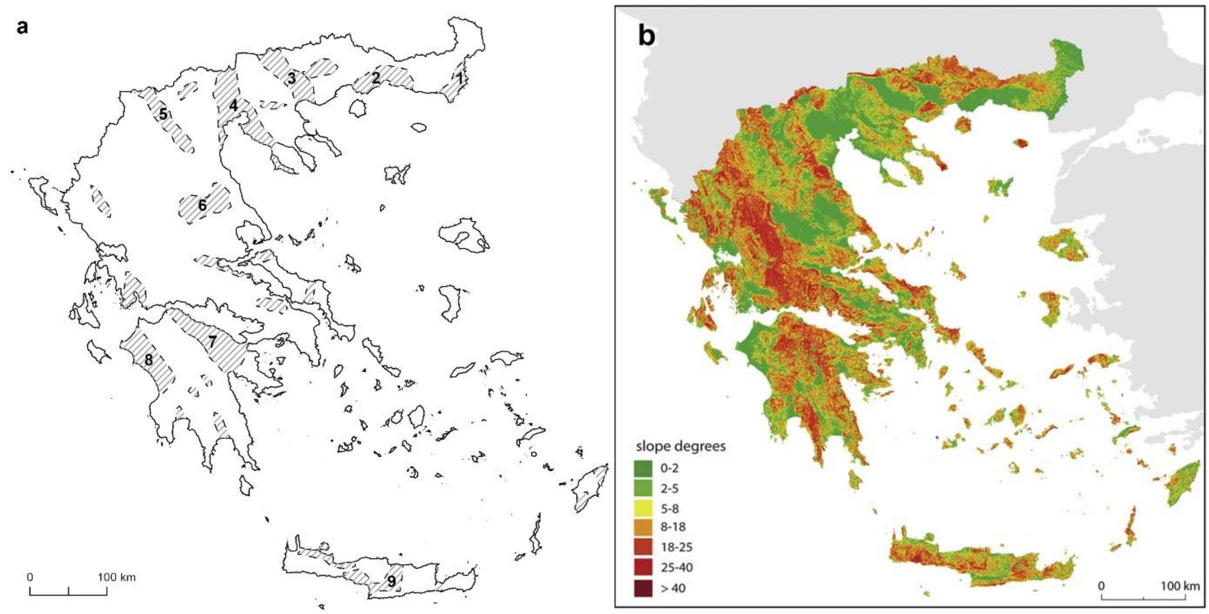

Figure 1. a) Main Neogene and Quaternary sedimentary basins of Greece (redrawn from Mountrakis, 2010), b) Slope map of Greece

Taking into account that the Neogene soil deposits fall mainly in the continuum from hard soils to soft rocks, in the present paper we have considered, as a start, only the Quaternary deposits and more specifically the Holocene subset of deposits encountered in Greece that are shown with green color in Figure 2. These soil deposits are primarily recent alluvial deposits encountered in valleys and plains. The map was produced in ArcGIS 9.2 (ESRI, 2006), based on data provided by the Hellenic Survey of Geology and Mineral Exploration (HSGME).

Figure 2 provides a good example of the different needs of professionals and educators. The basic geological maps of Greece (HSGME, 2015) have been available to practitioners and educators, for a fee, in 327 separate sheets covering all of Greece at a scale of 1:50,000, each sheet corresponding to an area of 18 by 22 kilometers. In principle, information could be extracted from these sheets to create a map like the one in Figure 2. However, to the authors' knowledge, there has not been an effort to produce, on a larger scale, a dedicated map showing only the occurrences of soil deposits. Perhaps such a large-scale map is of little use to the practitioner. But it is very useful for an educator in search of material suitable to motivate beginners (students).

The Quaternary (Holocene) deposits in Greece are mainly alluvial deposits, with some coastal deposits and, more seldom, lagoon and aeolian deposits. In general, soil deposits can be characterized as follows:

- Soil deposits with predominantly fine-grained particles (e.g. Case B in Section 4.2).
- Soil deposits with predominantly coarse-grained particles (Greece lacks deposits of significant extent of this type because their formation is connected with long periods of deposition in basins surrounded by relatively uniform bedrock, conditions that rarely exist in Greece).
- Soil deposits with mixed particle size, encountered usually in layers but with lateral variability (e.g. Case A in Section 4.1).

Figure 2. Outcrop of the Holocene subset of the Quaternary soil deposits in Greece (scale 1:1,000,000), (i) Aliakmon, Loudias, Axios, Gallikos rivers area and (ii) Sperchios river area

3.2 An attempt to put together some guidelines, both general and Greece-specific

After discussions with colleagues knowledgeable in geology, the second author has formed the impression that the guidelines on how geology can inform soil mechanics appear to belong in an “oral tradition”: when the question of references arises, none is offered. If this impression is wrong, it is hoped that the present article will offer an incentive for these references to be identified and for suitable examples to be put forth. For the time being, the following compilation of general guidelines is provided:

- Lake sediments and sea sediments tend to be fine grained and, compared with river sediments, more uniform.
- River sediments in flat valleys, e.g. the area of tributaries of main rivers in central Macedonia (Aliakmon, Loudias, Axios, Gallikos), are more uniform and fine-grained compared with river sediments deposited by rivers with steep gradients, e.g. Sperchios river, see Figure 2, areas (i) and (ii), respectively.
- Sediments at the shoreline of lakes are less uniform (i.e. more like river sediments) compared with lake sediments further away from the shoreline.
- The heterogeneity and lateral variation of the recent sedimentary deposits in Greece is mainly due to the high tectonic activity in the country; the resulting heterogeneity of the parent bedrock formations produces different soil types.
- The tectonic activity is responsible for the continuing uplift of large parts in the country, which created a varied morphology (abrupt changes in the terrain), thus allowing for high-energy depositional

environments. Additionally, Quaternary deposits with greater thickness are encountered near structural zones, i.e. active faults, where tectonic movement results in fault escarpments producing degraded material.

- Paleo-morphology features, like buried valleys or paleo-deltas, may result in large thickness of Quaternary deposits. Tectonic activity is associated with higher probability for the occurrence of buried valleys, which, however, may have been formed from non-tectonic processes, e.g. from a landslide that covered river sediments.

4 Case studies

This section contrasts two case studies, Case A (Section 4.1) and Case B (Section 4.2) involving mainly alluvial soils, at the locations shown in Figure 2. The case studies were selected as examples primarily of the relationship between the geological processes and the required information from boreholes and, secondarily, of anticipating the engineering behavior of the soil formations. The two case studies have different soil profiles. The first is a heterogeneous profile consisting of clays, silts and sands of fluvial origin and the second is a homogeneous profile consisting of fluvial fine-grained material.

According to the regulations of the Greek State, the design of engineering works is performed in different stages: a) preliminary design, for which an initial, usually limited, site investigation is performed, and b) final design, for which a more detailed investigation is executed that allows the designer to optimize the engineering requirements based on a more accurate ground model. In some cases, the preliminary investigation stage is skipped and only the final design is executed. The geotechnical investigation of Case A was at the stage of preliminary design. The design for Case B was performed in a single stage, i.e. the final stage.

4.1 Case A: Kyllini

Case A is an area along the new National Highway connecting Patras, Kyllini and Pyrgos in western Peloponnese, at the location of a future roadway bridge overpassing the railway line (coordinates 37°54'59.83"N, 21°16'0.55"E). The length of the concrete bridge is 310 m. It will be founded on nine (9) piers and be constructed with the cantilever method. As the site investigation in Case A was at a preliminary stage, the number of boreholes was limited only to the location of some of the piers, in order to make a first assessment of the foundation conditions. A final design stage would follow with additional ground investigation, before finalizing the structural design of the bridge. However, due to delays in the funding of the project, this stage has not been executed and the construction of the bridge has not started at the time of the writing of this article.

4.1.1 Geological background

The area of Case A is characterized by the alluvial Quaternary deposits of Peneus River ("Pinios" in Greek), the 3rd longest river in Peloponnese, which discharges into the sea in the broader Kyllini area, as shown in Figure 3. The area is characterized by Holocene terrestrial (i.e. including ground surface runoff and river flow) and torrential clayey and sandy deposits [geological map of Greece, scale 1:50,000, sheets Amalias (HSGME, 1977a) and Nea Manolas (HSGME, 1977b); Maroukian et al., 2000]. According to the Amalias sheet (HSGME, 1977a), the project area and a significant area around it are covered by "recent deposits: sands and grits in the area, sands and cobbles at the torrent beds". The torrential clayey and sandy deposits represent the most extensive Quaternary alluvial deposits in the Peloponnese. Primarily responsible for the accumulation of these deposits is the Peneus River, originating in the Arcadian Mountains to the east and entering the Ionian Sea south of Cape Kyllini (Figure 3). However, the palaeo-delta of the Peneus River is believed to have been located north-west of Cape Kyllini (i.e. north of the present river bed), giving rise to a sequence of lagoons and marshes embedded in the prograding delta and fed by sediments from the uplands of the Elis administrative region. The area is one of the most seismically and tectonically active regions in Greece, with a great number of changes during the morphogenetic events taking place mainly during the Quaternary period. Hence, a lot of variability is expected in the sediments of the Peneus River. The geology of the area is presented in Figure 3, based on the work of Haenssler et al. (2014).

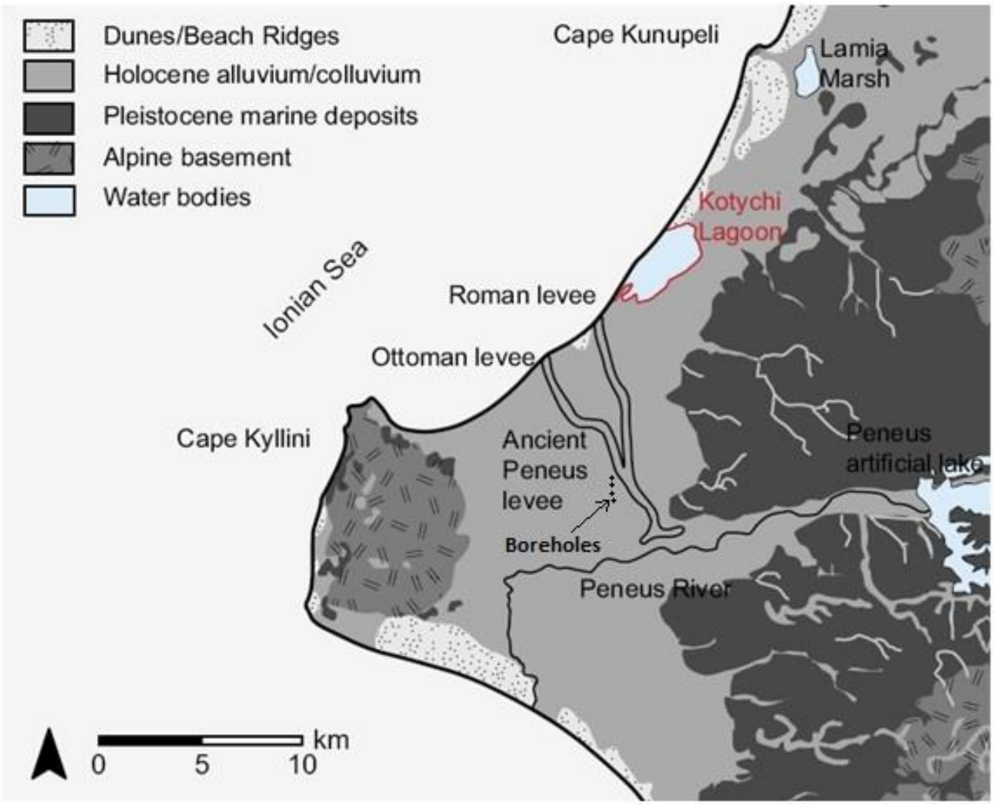

Figure 3. Outcrop Geology of the wider area of Case A, according to Haenssler et al. (2014) (figure published under Creative Commons Attribution 4.0 License)

4.1.2 Geotechnical investigation

A geotechnical investigation campaign was executed in order to perform the preliminary geotechnical design of the bridge foundation. At this preliminary stage, it consisted of only five (5) sampling boreholes up to a depth of 40 m below ground level (GL), located in the vicinity of five from the nine peers of the bridge. Figure 4 summarizes the findings from the five boreholes (BH1 to BH5), which were spaced about 85 m apart: the borehole findings show that the ground consists of a very heterogeneous profile in both the horizontal and vertical directions. A sequence of clays, sands and silts was encountered up to a depth of 35 m, overlying a horizon of dense sands. The lateral variability in the area is due to the deposition of different types of materials (fine and coarse), which belong to the fluvial and paleo-deltaic system of Peneus river. The following units (layers) were encountered:

- **Unit I**. Layers of light brown, low-medium plasticity, moderately stiff-stiff clays (CL) with intercalations of silty clays (CL-ML) to low compressibility sandy silts (ML), $N_{SPTmean}$ = 11.

- **Unit II**. Light brown, poorly sorted, dense sands (SP), $N_{SPTmean}$ = 50.

- **Unit III**. Clay of low to medium plasticity (CL): in some locations intercalations of silty clay (CL-ML) and low to medium plasticity silt (ML) are encountered, $N_{SPTmean}$ = 17.

- **Unit IV**. Stiff, medium plasticity clays (CL)-very stiff, high plasticity clays (CH), $N_{SPTmean}$ = 25.

- **Unit V**. Grey, poorly sorted, dense sand (SP) to silty sand (SM), $N_{SPTmean}$ = refusal.

Unit II (sands) was present only in two of the five boreholes (BH1, BH3) and the thickness of most units (especially Unit III and IV) varied significantly, resulting in lateral variations of the profile. This variation is characteristic for fluvial depositional systems, where different soil particles are found in the inner and outer banks of the river. The fact that the area of Case A is also very close to the paleo-delta, also explains the primarily fine character of the soil deposits at greater depth (Unit I, III and IV). Unit V is most probably the Pleistocene marine deposits underlying the Holocene fluvial deposits (Unit I to IV).

With the exception of the sandy layer consistently appearing at depth varying from 35 m to 38 m (Unit V), the area of Case A is characterized by significant heterogeneity with layers of varying thickness and lateral transitions. Thus, it was not possible to construct a geotechnical profile for the area, but only to have knowledge of the ground conditions at the vicinity of each borehole.

Following the ground investigation it was determined that the higher bearing capacity layer, Unit V consisting of sands, is located at a significant depth of approximately 35 m and, therefore, it was decided that the foundation would be designed with friction piles within the first three layers (Units I, II and III) reaching a depth of 20 m.

The understanding of the ground profile for the foundation conditions of the remaining four (4) piers would require either a detailed study and interpretation of the geology of the site or the execution of additional boreholes. As already mentioned, at the time of the writing of this article, the project has been halted for some time, so it is not known how the geotechnical investigation will proceed.

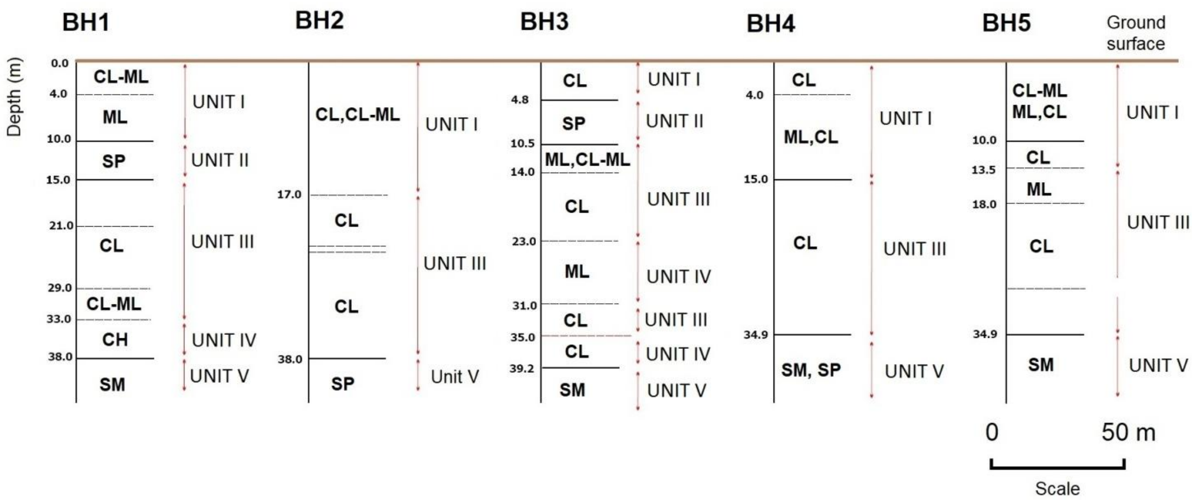

Figure 4. Ground profile in the area of the foundation of the bridge in Case A (adapted from General Consulting Ltd, 2003)

4.2 Case B: Evros

Case B is an area at the border of Greece with Turkey (called Peplos) along which the Evros River flows (coordinates 40°54'49.37''N, 26°16'35.03'' E). In this area an irrigation network of open canals was planned and the geotechnical design was required mainly for the foundation of the pumping station. The study area has a horse-shoe shape delineated with a yellow line in Figure 5. The total surface of the area that will be irrigated using water from the Evros River is 74 km^2. The irrigation is achieved through a pumping station that removes water from the river and transfers it first to a storage tank and then to the irrigation canals. The main canals run in the north-south direction, while secondary canals reach the entire irrigated area. The canals will be lined with precast concrete elements.

4.2.1 Geological background

Geologically, the area is characterized by the fluvial deposits of the Evros River and the deltaic sediments near its banks. The north part of the Case B area is dominated by silts, deposited nearby an earlier location of the river bed, which cut through the land protrusion near the center of Figure 5, i.e. the location of the project. The south part of the Case B area is dominated by clayey sands, which are associated with the current, meandering river bed and slower flow velocities that allow sand to settle. Based on Kanellopoulos et al. (2008), the depositional environment in the region is characterized by consistently low energy, thus mainly fine grained soils are expected, of uniform consistency with depth. The deposits originate from the erosion and washing out of older Quaternary formations and are deposited mostly during flooding periods.

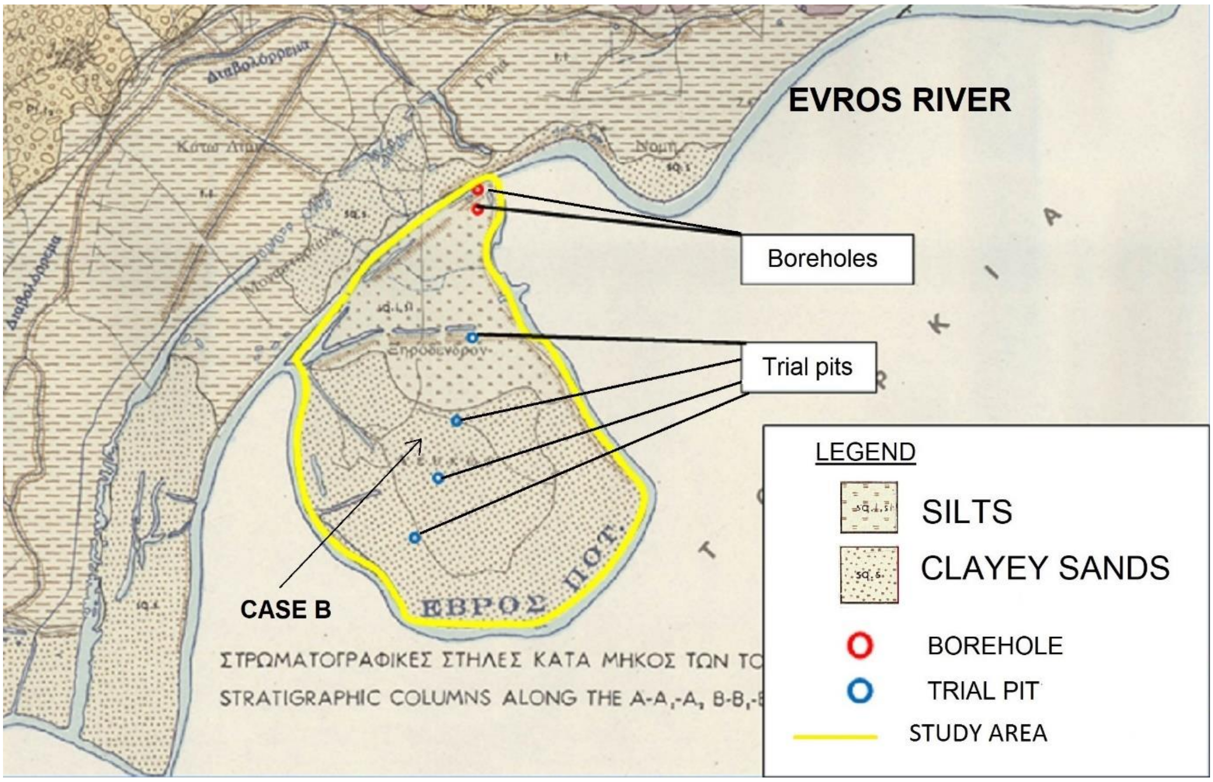

Figure 5. Geological map of Case B area at scale 1:50,000 (HSGME, 1980)

4.2.2 Geotechnical investigation

A geotechnical investigation campaign was executed consisting of two (2) sampling boreholes, located 150 meters apart, to a depth of 20 m below ground level, in order to design the foundation of the pumping station and the storage tank. In addition, four trial pits were excavated to a depth of 2 meters to design the irrigation canals. As already mentioned, the geotechnical investigation fell within the scope of the final design of the project.

Based on the findings of the boreholes, it was evident that the ground profile was homogeneous, with practically no variation in the types of soils. The following units (layers) were encountered:

Unit I (brown-grey) and **Unit II** (grey), 0 to 8m, soft clay of low plasticity (CL) $N_{SPT\ mean} = 4$.

Unit III, 8, to 20m, grey stiff clay of low plasticity (CL) $N_{SPT\ mean} = 13$.

The geological history of the area and the information from the boreholes both point to a uniform ground profile, consisting primarily of fine sediments. Moreover, as these sediments are relatively recent, it is anticipated that the soil shear strength and stiffness increase linearly with depth.

5 Concluding remarks

The motivation to put together this paper was to claim a space for soils within engineering geology and sketch suitable educational material. In order to claim a space for Greek soils in particular, the authors sought the information necessary for depicting the areal extent of the recent Quaternary (Holocene) deposits encountered throughout Greece, as a first step towards producing a soil deposit map for Greece. The paper discussed in the form of general guidelines how the knowledge of the geological setting and depositional conditions of a specific area helps anticipate some general features of the ground profile. At the very least, the depositional history can guide us to expect homogeneous or heterogeneous soils.

The knowledge of local geological conditions and history of a specific site can assist in understanding the complexity of the ground profile and therefore provide vital information to determine the appropriate geotechnical investigation campaign. When significant lateral and vertical variation of the soil profile is expected, it is advisable not only to increase the number of boreholes but also perform a detailed geological study to build a more accurate ground model. The type of investigation of course is also determined by the design stage of the project, whether preliminary or final.

Two case studies, A and B, were selected to further demonstrate with examples the influence of the depositional environment on the expected heterogeneity. The sediments in both cases were alluvial, but they differed in terms of depositional energy and tectonic activity, which where both higher in Case A, resulting in variations in morphology and in the consistency of the parent bedrocks. In Case A, the ground profile was very variable due to sedimentation in a highly active tectonic area. In Case B, the ground profile originated from deltaic deposits in a relatively low-energy depositional environment, thus the deposits were homogeneous, as expected in such environments. The implications of these two contrasting profiles for the design of a ground investigation campaign is that complicated profiles, such as that in Case A, require a larger number of boreholes in order to determine the design profile for a sizeable infrastructure project, such as a bridge foundation.

In summary, the authors attempted to capture the relationship between Engineering Geology with Soil Mechanics through a few suggested general guidelines and two case studies. Their ultimate goal is to create a common frame, which the engineering geology and geotechnical engineering communities can modify and expand upon.

Acknowledgements

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