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Implementing a Static Cone Penetration Test in Infrastructure Works

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Abstract

In modern era, a construction of infrastructure projects necessitates a geotechnical investigation, which usually involves the execution of boreholes and laboratory testing on their samples as well as in-situ testing. A useful test, important for both educational and practical reasons, is the Cone Penetration Test (CPT), used to estimate the strength and compressibility of loose-to-medium dense coarse grained and soft to stiff fine-grained geomaterials, the excavation of which requires special attention. In this paper, a theoretical review on geotechnical surveys, in-situ testing of static cone penetrometer, statistical analysis of results, geotechnical correlations for the evaluation of results along with a dimensioning of the retaining wall with pile boards, is presented. The paper aims at highlighting the use of CPT for selecting the proper type of the temporary retaining structure, necessary to support excavations in loose-soft soils. The case study includes a pump room construction along with its aqueduct, close to Aliakmonas River in Greece. From this point of view, it may offer a rather powerful research design basis than purely experimental methods.

Keywords: Geotechnical investigation; infrastructure planning; pump room; retaining structure; sheet piles; site investigation.

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1. Introduction

In recent years, the application of in-situ tests in geotechnical investigation is expanding due to improvement of tools (e.g. electric cone) along with the development of new types of instruments and tests. This holds particularly in Greece, where soil is highly heterogeneous, with various difficulties in obtaining not only undisturbed samples but also samples that can be considered as representative of soil mass, in-situ tests [1]. The extent of geotechnical investigation varies according to the importance of the project to be constructed, the peculiarities of the foundation subsoil conditions and the behaviour of existing structures based on similar soils. The development of infrastructure in Greece (transport, water, drainage, irrigation) has led to the construction of pump rooms in close proximity to the sea, rivers or lakes. For the realization of these projects, most of which are underground, a deep excavation is usually required, well below the ground water table. Therefore, provisions should be made for a construction of temporary retaining walls. A design of such walls involves the execution of a geotechnical investigation, which, in the case where the subsoil at the project site consists of soft – loose soils, it can be conducted using the in-situ Cone Penetration Test (CPT) [2]. Its analysis is based on theoretical considerations rather than on empirical data. The contribution to research coming from this test, concerns the applicability of ordinary interpolation of the CPT results, as the whole soil profile is directly obtained, instead of estimating its value at a specific depth. This study presents the methodology of geotechnical investigation through the CPT along with the evaluation of data obtained from the corresponding results. Then follows the geotechnical design for the temporary retaining structure, which is required for the foundation and the pump room construction [3]. Characteristic photographs were also taken during the different stages of construction.

2. Literature review and methodology

The article is linked to bibliographic references, while advantages of the CPT method with respect to other drilling methods and specially the Standard Penetration Test (SPT) are presented. The methodology used to organize the necessary work is also developed in detail. In a deductive approach, researchers use theory to guide a design and interpret the corresponding results. As researchers continue to conduct empirical research to confirm a theory, they develop a confidence which comes as a result of the theoretical truth. Since natural soil behaviour is complex, any classification system based on behaviour characteristics should involve multiple measurements that are repeatable and cover different aspects of in-situ soil behaviour. For a classification system to be effective and easy to use, it must be based on rather simple, cost-effective repeatable tests. For an in-situ test to meet these demands, it should be simple, affordable and provide several repetitive independent measurements. One of the most popular, modern in-situ tests that are applicable to uncemented soil is the Cone Penetration Test. It is fast (20 mm/s), cost effective, and provides continuous and repeatable measurements of several parameters. The basic CPT, records tip resistance (q_c) and sleeve resistance (f_s). The CPT_u provides an additional penetration pore pressure (u), often in the u_2 location just behind the tip, combined with a measure of the rate of pore-pressure dissipation during a pause in the penetration process, often expressed as the time required dissipating 50% of the excess pore pressure (t_{50}). The CPT_u can also provide in-situ equilibrium pore pressure after 100% dissipation (u_0), which is helpful to define the in-situ piezometric profile at the time of the CPT_u. The seismic CPT_u ($SCPT_u$) provides the additional measurement of in-situ shear wave velocity (V_s) and, in some conditions, in-situ compression wave velocity (V_p). Hence, the CPT_u can provide up to seven independent measurements in one cost-effective test. Ideally, a classification system should include all these measurements to be fully effective. However, a practical classification system can still be effective based on either two or three measurements, provided limits are placed on the range of applicable soils (e.g., restricted to predominantly ideal soils). The cone penetration test has been gaining popularity for site investigations due to the cost-effective, rapid, continuous, and reliable measurements. The most common CPT-based classification system is based on behaviour characteristics and is often referred to as a soil behaviour type (SBT) classification [4]. More specifically it has been shown by Robertson, that the $SCPT_u$ measurements have the potential to identify soils with significant microstructure. For a geotechnical soil investigation, CPT is more popular compared to SPT and other Geotechnical boring or drilling methods. Its main properties include increased accuracy, speed of deployment, more continuous soil profile and reduced cost with respect to other soil testing methods. Furthermore, an advantage of the CPT over the SPT is a more continuous profile of soil parameters, with data recorded at intervals, typically of 20 cm, but as small as 1 cm [5]. The ability to advance additional in-situ testing tools using the CPT direct push drilling rig, including the seismic tools described above, only serves to accelerate this process. Though both Geotechnical Boring and CPT provide suitable options for obtaining useful information, there are many more benefits to using CPT over Geotechnical drilling. CPT is not only a cost-effective option, but also provides immediate electronic data for review. Most of the other in-situ methods allow estimations of some properties, applicable at limited conditions and circumstances. Reliable results, continuous data, irreplaceable status at certain soils, higher safety can be additional advantages of the test. Not only is CPT a better option for a professional approach, but usually it is a lower cost solution while delivering more data [6]. It should be mentioned that references 1, 4, 6, 7, 8, 9, 10, 11 and 14 from the literature provide data on the necessity of use as well as the mode of operation of the CPT method and present (mainly 4 and 6) the advantages of this method with respect to other on-site drilling setups. Furthermore, references 3, 5 and 13 give data for the construction site of the project along with the method's drilling regulation. Finally, references 2 and 12 present the way of choosing sheet piles, based on the results of the CPT method, as well as the method through which the conductor duct and the pumping complex should be constructed. Concluding, this study exhibits the methodology of a geotechnical investigation through the CPT, along with the evaluation of the data obtained from the corresponding results. Presented next is the geotechnical design of temporary retaining structure required for the foundation along with the pump room in a riverside area, followed by photographs taken at different stages of construction.

3. Materials and methods

3.1. The Cone Penetration Test

The CPT may appear in two different forms, dynamic and static, briefly and schematically described below in Figure 1.

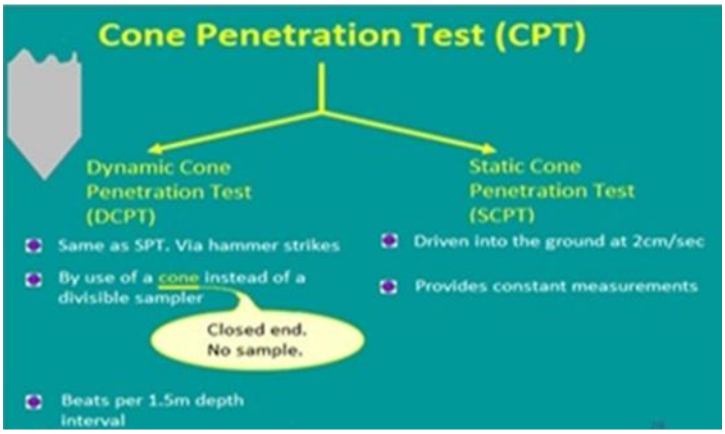

Figure 1: The Cone Penetration Test [7].

3.1.1. Dynamic penetration test

This is a penetration of a standard cone caused by weight impacts, free-falling from a specific height. The results include plotting the number of impacts (for a set penetration depth) as a function of the depth. No soil sample is taken.

3.1.2. Static penetration test

A standardized test which provides mainly charts of variation in cone resistance of the standard cone, as a function of depth, when penetrating the ground. There are several types of cone with a choice between a mechanical one (Dutch cone described by specification E106-80.9), and an electric cone - piezocone (while measuring pore pressure). The above tests provide detailed information on soil stratigraphy, allow preliminary estimates of geotechnical properties, liquefaction risk estimates and are performed in accordance with E106-86 par.9, ASTM D 3441-98. The cone penetration or CPT is a method used to determine the geotechnical properties of soils and delineate soil stratigraphy. It was initially developed in the 1950s at the Dutch Laboratory for Soil Mechanics in Delft to investigate soft soils. Based on this history it has also been called the "Dutch cone test". Today, the CPT is one of the most used and accepted soil methods for soil investigation worldwide. More specifically, static penetration testing is used to measure the undrained shear strength of soft to stiff clays and the relative density of sand. The test is based on the continuous advancement (speed 1- 2 m/min) of a cone with a 60-degree apex angle and a cross-section of 10 cm^2. During the penetration of cone, the resistance caused from cone advancement and lateral friction on the cylindrical jacket having a surface area of 100 cm^2 is measured. The CPT is performed today with "electric cones", in which the measurements are taken by means of electrical converters and are automatically recorded in analog or digital mode. A pressure gauge is often placed in the base cone area to measure the pore pressure developed during the penetration of the cone [8]. Figure 2 shows a complete cone penetration system.

Figure 2: Hydraulic cone penetrometer system [9].

The change of resistance developed with the depth during the penetrometer's soil advancement and the variation in the pore pressure that appears on the cone area are measured by manometer devices which lie on the instrument console or they are built in one of the cone sensors (modern penetrometers). Sensor data are transmitted via electrical wiring to the controller where they are automatically recorded as shown in Figures 3 and 4 [10].

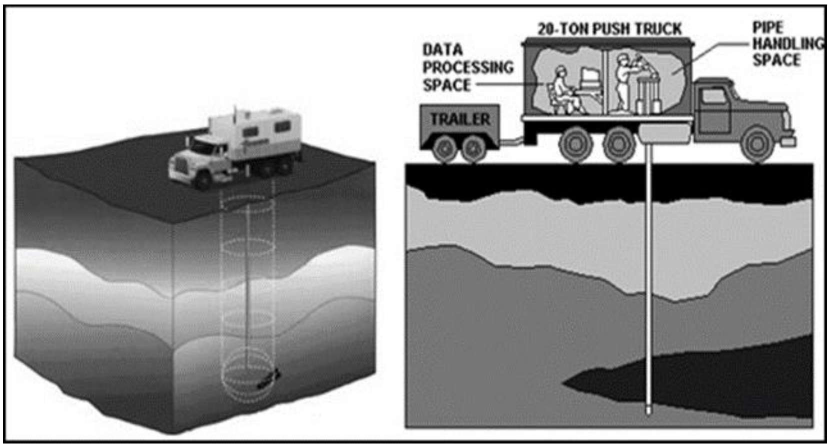

Figure 3: Representation of static cone penetration test [10].

The test is carried out without sampling and consequently the stratigraphy of the soil should be deduced from the corresponding measured results (Figure 5).

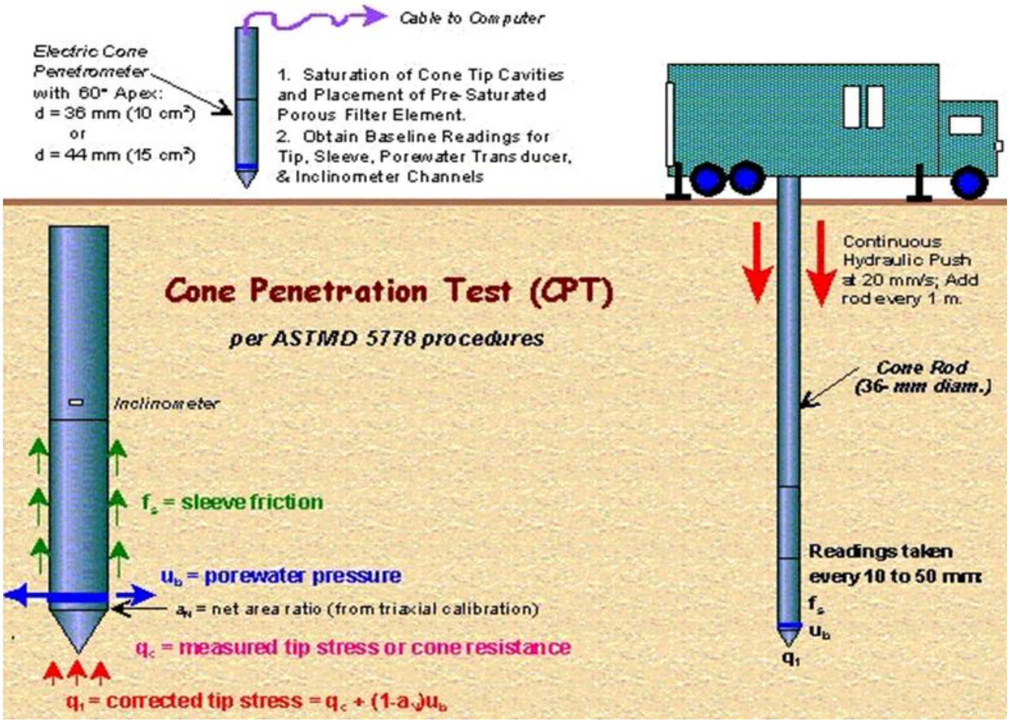

Figure 4: Cone penetration test [11].

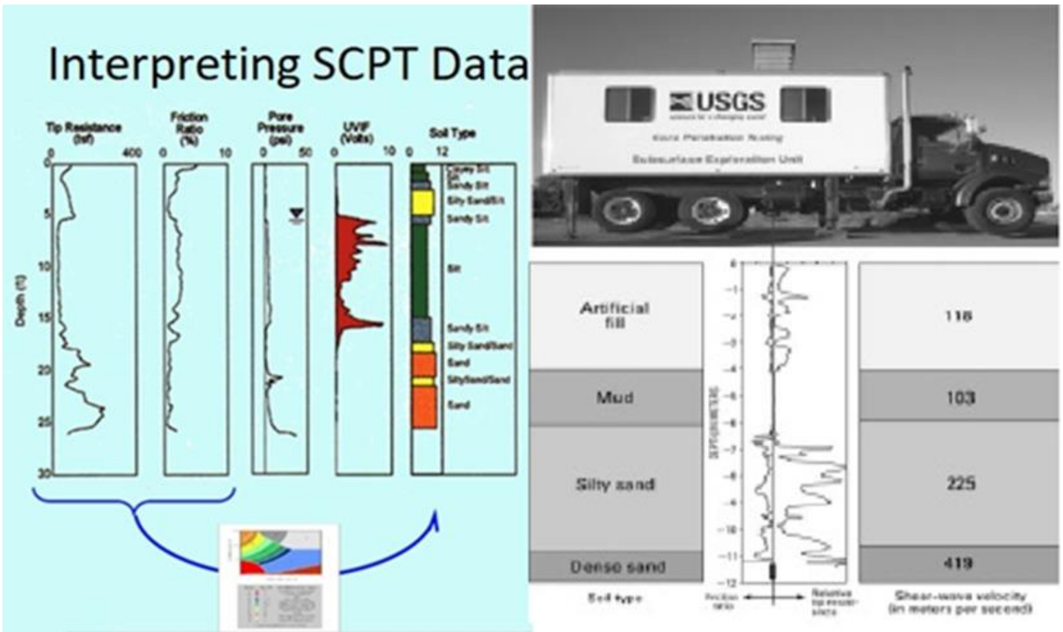

Figure 5: Interpretation of CPT data [10, 12].

From measurements of the cone tip resistance, q_c, combined with lateral friction, f_s and the developed pore pressure, u_s, along with acquired experience and calibration from tests next to boreholes of the project area, engineers extrapolate the stratigraphy and consistency/relative density of soil formations (Figure 6).

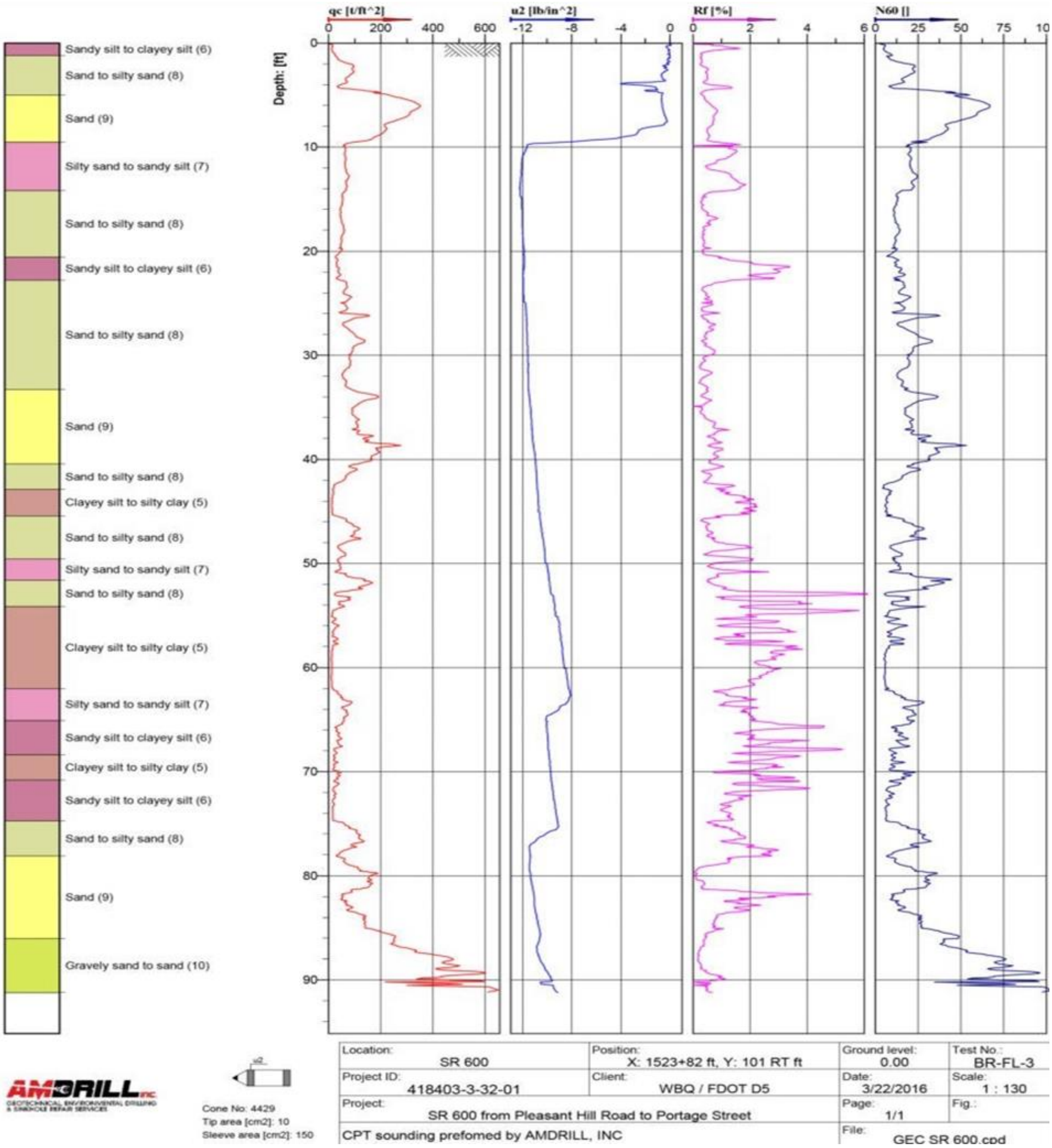

Figure 6: Cone penetration test, site exploration and characterization [11].

The main advantages of the test are the execution speed and continuous recording of soil engineering characteristics with depth, while a drawback is that no soil samples are taken. The test cannot be used in gravelly soils or hard clays because the cone is not able to penetrate these soil formations [8].

During the test, the following parameters can be measured by means of appropriate manipulation:

- Tip resistance q_c
- Local, unitary lateral friction resistance f_s
- Friction ratio $R_f = f_s / q_c$

- Friction index $I_f = q_c/f_s$

The advantages of the CPT method, in brief are:

- The CPT method is reliable on recording the variability of in-situ density of loose sandy soils and clays due to soil not being disturbed during its execution
- It is also reliable on continuous recording of subsoil stratigraphy and soil characteristics by depth
- CPT is a fast test with high execution speed and fewer operating errors compared to SPT
- It can be applied for investigation in loose - medium dense sandy soils - soft to stiff clay soils
- The method is widely used in-situ tests with significant reliability, immediacy, speed and relatively low cost [7]
- CPT is a test of high-quality geotechnical exploration and continuous data acquisition of subsurface profiles
- Furthermore the method offers the latest on CPT performance in geotechnical engineering, i.e., bearing capacity, settlement, liquefaction, soil classification and shear strength prediction.

Similarly, the disadvantages are:

- No soil samples are taken.
- The test cannot be used on gravelly soils or hard clays dew to inability of the cone to penetrate these soil formations.

3.1.3. Comparison between onsite CPT and SPT penetration tests

For a geotechnical soil investigation, the CPT method is more popular compared to SPT. This is because its increased accuracy, speed of deployment, more continuous soil profile and reduced cost are important parameters. The ability to advance additional in-situ testing tools using the CPT direct push drilling ring, including the seismic tools, only serves to accelerate the process.

3.2. Ground investigation for selecting the appropriate type of the retaining structure

An application in using the results of cone penetration testing for the construction of both a retaining wall and a pump room is presented. The aim of the geotechnical investigation was to determine the prevailing subsoil conditions at the site, i.e. stratigraphy and characteristics of subsoil layers and groundwater level. On the basis of these data, documented proposals were put forward, regarding the selection of an appropriate retaining structure for supporting the temporary deep excavation required for the foundation of the pump room and its aqueduct, thus preparing the geotechnical design.

3.2.1. Geological and seismological data of the wider local area

The case study of the present work refers to the construction of the pump room along with the aqueduct, followed by the ground survey, which was done through the CPT method. The exact location of the project was pinpointed on a geological map sheet, coming from the Geological and Mineral Exploration Institute (IGME), were, information on the geological formations of the project area were collected. According to the geological data of the IGME, the subsoil in this region consists of Holocene deposits "H" (fine-grained sands, clays, sandy clays and clayey sands, as well as sediments from small and ephemeral marshes). Furthermore, the results of geotechnical investigations carried out in the greater regional area (Kalohori, Sindos, Prefecture of Thessaloniki) were also sought, especially those on Holocene deposit soils. It was found that these soils consisted mainly of soft to medium cohesion clays – silty clays, as well as loose to medium dense silty clayey sands – sandsilts, with slow water permeability, and pH ranging from 7.3 to 7.9 in alkaline soils. Finally, referring to the provisions of the Hellenic Seismic Regulation 2000 (as amended by Government Gazette 1154B, 12-8-2003), the project area belongs to a zone of seismic hazard I, with a peak ground acceleration α = 0.16g (where g is the gravity acceleration) and a probability 10% of being exceeded in 50 years.

3.2.2. Geotechnical investigation

Having considered the geological formations of the area (Holocene deposits consisting of soft to medium consistency clays – clayey silts – loose – medium dense clayey silty sands – sandsilts), the geotechnical investigation was decided to be carried out by means of an in-situ static cone penetration test as the low strength-density of soil formations permits the cone to penetrate at great depths. On the spot access roads were locally found. Eventually, it was concluded that a truck weighing 20 tons, carrying the apparatus required for the in-situ static cone penetration test (push rods, manometers, dynamometers) was able to access the project site, in order to perform the test.

4. Geotechnical investigation results

The ground investigation at the project site was carried out through a static P-1 cone penetration test, at a depth 42.6 m from the temporary working floor of the project, which, at that time, was at a depth of 1.5 m from the surface of natural ground, as shown in Table 1 below.

Table 1: Cone Penetration Test data [3]

CPT	Investigation depth from natural ground (m)	Investigation depth from working level, 1.5m deeper than natural ground	Depth of ground water table from the natural ground (m)	Depth of ground water table from working floor level (m)
P-1	44.1	42.6	2.8	1.4

Cone penetration test was carried out by a 20-ton motor penetrometer truck of the A.p.v. den Berg type, with a cone penetration rate (speed) of 2 cm/sec. A Begemann-type Dutch cone was used during the test, which allows for recording the force acting on the cone, the total load to push the column (cone's tip and push rods) into the ground, and the force necessary to push both the sleeve jacket and the cone. From the above measurements, the following parameters are constantly derived with respect to depth: a) the tip resistance of the cone q_c and b) the local lateral friction f_s between the cone's sleeve jacket and the surrounding soil. These parameters are discussed in detail in a subsequent paragraph. The friction ratio $R_f = f_s/q_c$, is calculated from the value of the corresponding cone tip resistance q_c and then, through empirical nomographs like the one in Figure 8, the composition of soil layers can be estimated.

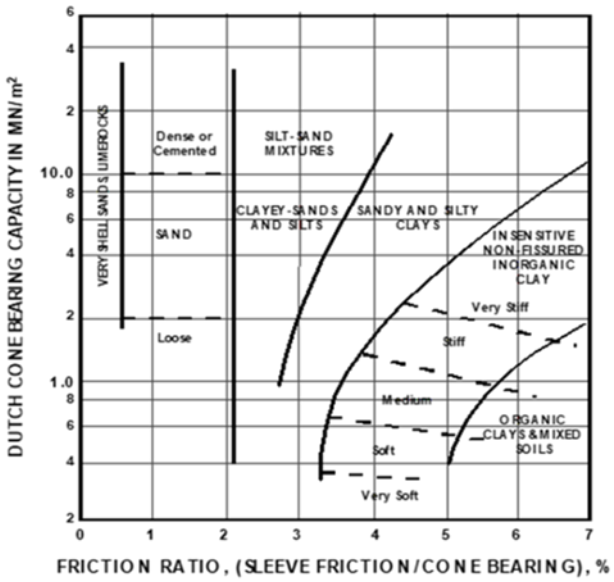

Figure 8: Nomograph for characterizing a soil formation as a function of tip resistance and friction ratio using a static penetrometer with a Begemann Dutch cone [12].

The results of the cone penetration test are presented in detail below (Figure 9).

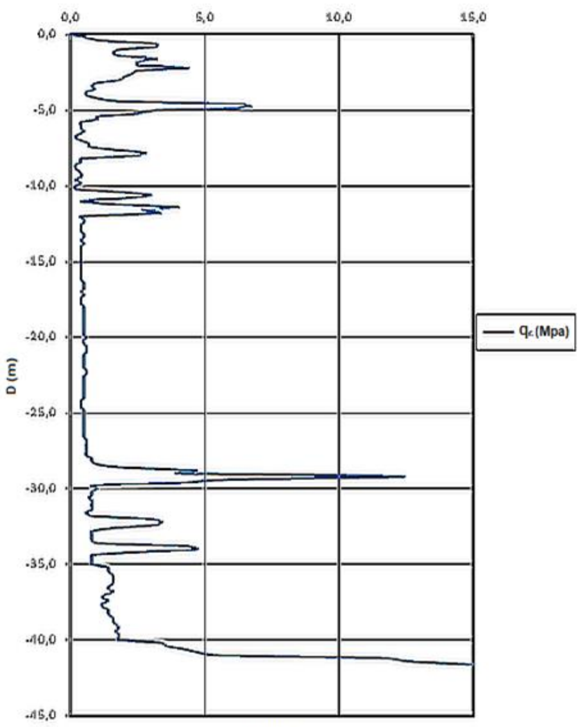

Figure 9: Change of tip resistance q_c (MPa) with depth D (m) [12].

The values of soil parameters for the different layers, like active angle of internal friction φ′, the undrained cohesion c_u and the soil compressibility modulus E_s are indirectly derived from the corresponding cone penetration test results based on well established, worldwide-used correlations of literature, while the apparent unit weight of soil, γ, is estimated on the basis of the macroscopic description of the layer and its estimated density. Based on the aforementioned data and following an analytic statistical processing of the SCP test results grouped by soil layer, a typical soil profile was composed, which was used for designing the temporary retaining structure, necessary to support the excavation for the project's aqueduct construction (Table 2).

Table 2: A typical soil profile [3].

Depths from natural temporary ground (m)	Temporary working floor (-1.50 from natural ground)	Depths from working floor (m)
1.50		0.00
G.W.T. 2.90	Layer "Cs": Clay to sandy clay – clayey silt, stiff to loose clayey sand $q_c \geq 2.1$ $\gamma \approx 18.5$ $C_v \geq 60$ $c' \approx 5$ $q_c \geq 2.4$ $\varphi' \geq 30$	G.W.T. 1.40
4.50		3.00
	Layer "C1": Medium consistency clay $q_c \geq 0.67$ $\gamma \approx 18.0$ $\varphi' \geq 29$ $c' \approx 3$ $q_c \geq 0.82$	
5.70		4.20
	Layer "CS1": Medium dense clay sand $q_c \geq 2.22$ $\gamma \approx 19.0$ $C_v \geq 33$ $c' \approx 0$ $q_c \approx 3.67$	
6.70		5.20
	Layer "C2": Soft clay with clayeysilty sand interlayers $q_c \geq 0.46$ $\gamma \approx 18.0$ $C_v \geq 20$ $E_s \approx 2.0+3.2$ (≈2.6) $q_c \approx 0.49$ $\varphi' \approx 28$ $c' \approx 2$	
11.70		10.20
	Layer "CS2": Soft to medium consistency clay, with loose clayeysilty sand interlayers $q_c \geq 1.55$ $\gamma \approx 18.0$ $C_v \geq 25$ $E_s \approx 4.4$ $q_c \approx 2.20$ $\varphi' \geq 28$ $c' \approx 4$	
13.30		11.80
	Layer "C2": Soft clay $q_c \geq 0.46$ $\gamma \approx 18.0$ $C_v \geq 25$ $E_s \approx 2.6+3.4$ $q_c \approx 0.48$ $\varphi' \approx 28$ $c' \approx 2$	
30.10		28.60
	Layer "C3": Medium consistency to stiff with depth clay to sandy clay - claysilt with local loose to medium dense clayeysilty sand interlayers $q_c \geq 1.41$ $\gamma \approx 18.5$ $C_v \geq 45$ $E_s \approx 6.2+8.3$ (≈7.3) $q_c \approx 1.59$	
42.50		41.00
	Layer "S": Medium dense to dense clayeysilty sand $q_c \geq 14.6$ $\gamma \approx 21.0$ $\varphi' \geq 38$ $E_s \approx 50.0$ $q_c \approx 18.1$	
≥ 44.10	-′′-	≥ 42.60

Legend: G.W.T.: Ground water table, q_c: Static penetrometer tip resistance (MPa), γ: Apparent unit weight (kN/m^3), φ': Effective angle of internal friction (Deg), c': Effective cohesion (kPa), c_u: Undrained shear strength (kPa), E_s: Compressibility modulus (MPa)

In brief:

The aim of this work is to present a case study highlighting the usefulness of the CPT method, through which we obtain results for the internal friction angle and the bearing capacity of the soil (Table 2). Then, making use of the Eurocode, we select the cross-section of the sheet piles that are necessary to support the excavation ground, along with the Scale beams and the Walling – struts necessary to fix and consolidate the above sheet piles. Therefore we can seamlessly build the pumping station (pump room), which is the ultimate goal.

4.1. Temporary excavation support for foundations

Taking into account the composition of the excavated soil (loose to medium dense sandsilty - soft clayey subsoil), the high groundwater table level, as well as the increased depth of temporary excavation, the support retaining structure of the slopes of the excavation was proposed to be materialized by the use of steel sheet piles. This solution was best suited to restrict groundwater to inflow from the slopes into the excavation. The total length of the sheet piles was chosen to be L = 8.0 m, of which 0.5 m remained above the surface (for construction and installation reasons), while the rest, 7.5 m, was embedded in the ground prior to construction. Additionally it was decided to place a series of steel struts and walling at a depth of 3.8 m from the surface of the natural soil (or at a depth of 1.0 m from the final working floor which was formed at a depth of 2.8 m from the surface of the natural soil). For the static analysis of the retaining structure, a finite element code was used considering two-dimensional plane deformation conditions. The analysis was carried out for cases B and C in accordance to Eurocode 7, by “Wallap” computer program of “Geosolve”. Based on the static analysis results, the dimensioning of the temporary retaining structure system was realised selecting St Sp 37 (S 240 GP) steel piles with a σ_{al} = 140.000 kN/m^2 and HEA 280 steel struts. This retaining structure system is shown in Figures 10 and 11.

Constraints \ Limitations:

As mentioned previously, the CPT method is widely used to estimate the soil properties, which in turn led to the choice of the Sheet piles cross-section along with the Scale beams and the Walling – struts. All the above calculations obviously refer to a granular (i.e. non coherent) soil. However, the method can be used with a satisfactory approach in clay soils (i.e. cohesional soils).

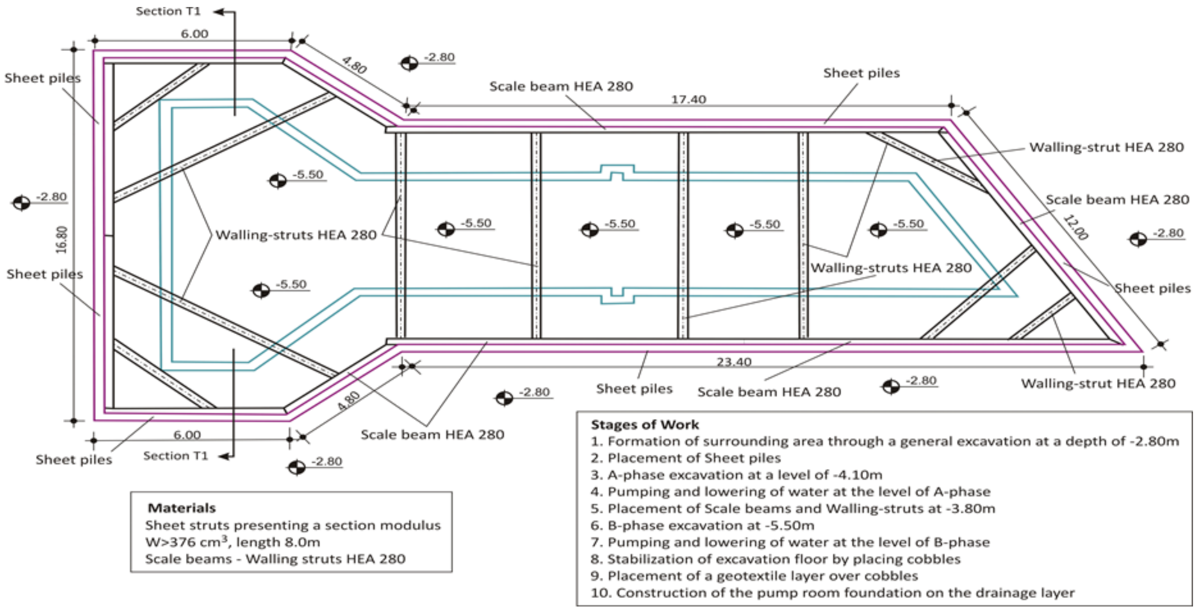

Figure 10: Top of the retaining system [2].

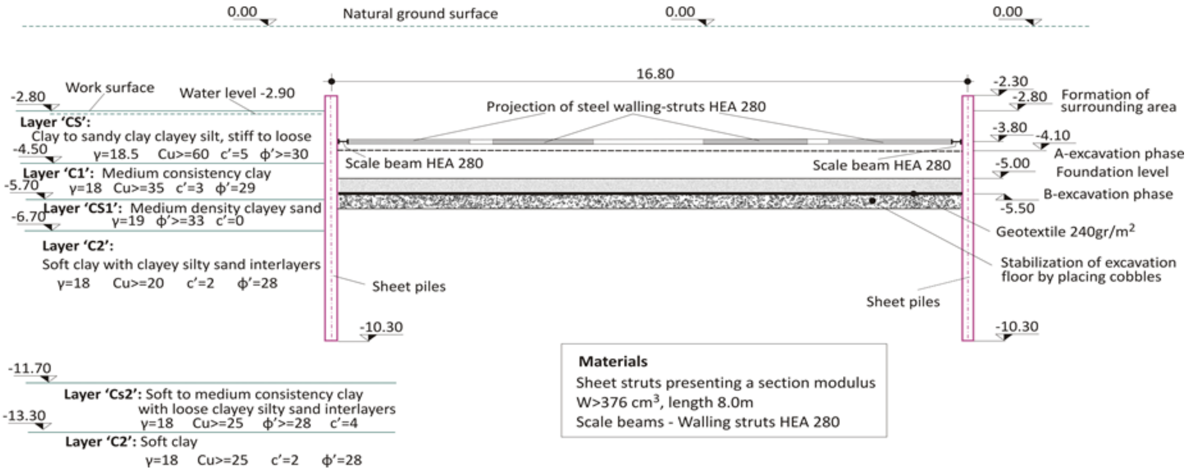

Figure 11: Section T-T1 [2].

4.2. Construction of the pump room and aqueduct

Initially the project area was formed through a general excavation at a depth of -2.8 m, after which the sheet piles were placed, as defined in the arrangement of Figure 10. Then phase A of excavation followed, which was carried out at the level -4.1 m, bounded by the sheet piles. Subsequently, a groundwater pumping was realized at this level of excavation. This stage was followed by the placing of the HEA 280 steel walling struts at a depth of -3.8 m. Then phase B of the excavation was carried out at a level of -5.5 m. A pumping and lowering of the water level until the level of excavation floor was the next step. The completion of excavation was followed by the placement of cobbles inside the excavation floor in order to stabilize it, and then a geotextile was placed over the layer of the cobbles, –creating a drainage layer, on which the foundation of the pump room and the aqueduct was concreted, as it is clearly shown in Figure 11. Various stages of the construction are depicted by photos (Personal archive of the geotechnical engineer M.Sc, I. Baloukas).

5. Conclusions

The whole implementation process as a useful tool for geotechnical investigation arising from this presentation had a clear reference to the Cone Penetration Test (CPT). Therefore, the most important conclusion to be drawn is to highlight the advantages of the CPT method that was meticulously applied in practice, thus helping greatly in compiling the geological profile and selecting the support sheet piles which in turn lead to the construction of a pump room and an aqueduct in the region of Aliakmonas River Delta. Therefore, the following useful conclusions arise:

- The CPT test is a reliable method for continuous recording of subsoil stratigraphy along with soil characteristics with depth.
- The most effective means for characterizing a complex site includes a thorough background examination, followed by a well-conceived program of subsurface exploration that commonly includes small diameter borings. Cone penetrometer soundings are being employed with increasing regularity, especially in the evaluation of soil liquefaction potential [14].
- The CPT procedure is capable of detecting discrete horizons that would normally be missed using drive samples at specific depth intervals [14].
- The CPT test was performed with great success in the relatively soft and loose soil formations in the area of Aliakmonas project and gave results on which the best type of soil retaining structure was based and chosen.
- The materialization of the temporary retaining structures on the slopes using sheet piles was very successful, taking into account, not only the low consistency and strength of the excavated soil but also the high level of groundwater table along with the deep depth of temporary excavation.
- The retaining structure solution reduced the inflow of groundwater into the excavation, thus making it easier to lower the level of groundwater below the level of the excavation floor through pumping.
- The provision for the installation of a series of HEA 280 struts and walling at a depth of 3.80 m below the surface of the natural soil, proved to be particularly beneficial, since their presence aided in the reduction of the embedded depth of the sheet piles along with a decrease on their bending stress magnitudes, in relation to a simpler solution of cantilever sheet pile retaining structure (without struts).

It is therefore confirmed that the CPT method involves a widespread in situ test with significant reliability, immediacy, speed and relatively low implementation costs.

6. Recommendations

It would be particularly interesting if a set of tests could be performed by the CPT method, however not in homogeneous, but in soils whose properties present a spatially variability. Through this way, we would have a more accurate estimate of the values corresponding to the properties of the soil, and therefore the stability coefficient of the soil mass whether it is a slope, or the estimate of the bearing capacity of the soil when it bears structural loads [15].

Placement of piles.

Installed pile series.

Phase A excavation.

Placement of steel walling – struts.

Installed steel walling – struts.

Phase B excavation.

Aqueduct floor construction.

Aqueduct wall construction.

Aqueduct walls.

Completed project.

Figure 12: Construction stages.

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