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CPTU onshore testing with pre-drilling and/or re-drilling of the ground at the Port of Barcelona. Lessons learned

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ABSTRACT

SOCOTEC Spain, together with our partner GEM (Geotecnia y Exploraciones Marítimas), has been performing one of the largest geotechnical survey investigations in the development of new areas in the Port of Barcelona. This investigation includes multiple onshore and offshore tests including drilling and sampling, CPTU, and both in situ and laboratory testing. The CPTU (Cone Penetration Test with pore pressure measurement) is currently one of the most widely used in situ tests for soil characterization. Regarding the regularization of this test, all Standards specify the technical requirements of the equipment, the method of execution of the field test and the presentation of results and minimum corrections that have to be considered when performing and interpreting a CPTU. However, the current regulations do not refer to the methodology to be followed for the pre-drilling and/or re-drilling of the ground before a CPTU test, which is a common and operationally 'standard' procedure. In this sense, during the onsite research campaign, the results obtained in numerous onshore and offshore CPTU tests have been analyzed and, a variation in the pore pressure data recorded in the onshore CPTU tests associated with the pre-drilling and/or re-drilling operations has been identified. For this reason, the purpose of the paper is to highlight the need for a standardized procedure to execute this type of drilling operations and/or the necessary corrections to be taken into account during the interpretations of the results obtained in order to correct the anomalies associated with the injection of an artificial water flow.

Keywords: CPTU/piezocone; pre-drilling; hydraulic gradient; dissipation test.

1. Introduction

The CPTU (Cone Penetration Test with pore pressure measurement) or piezocone test is currently one of the most widely used in situ tests for the characterization of soils in both terrestrial and marine environments and, in contrast to other tests, it allows the continuous evaluation of some of the main geotechnical characteristics, either in granular or cohesive soils.

However, even if the geology of the area is known and uniform, it is recommended to support these CPTU tests with other tests, such as mechanical boreholes with continuous core drilling or other tests, whether in situ or in the laboratory *(Lunne et al., 1997)*.

Thus, the execution of CPTU tests should not be systematized, they should be performed by appropriately qualified personal, who have high technical, geological and operational judgement, and are able to interpret almost instantly the quality of the recorded data, its validity and, in some cases, the integrity of the equipment.

From a normative point of view, the CPTU test is governed by several international standards such as, for example, the European standard UNE-EN ISO 22476-1, in the United States and Canada the ASTM D5778-12 standard, in France the NF P94-119 standard or in Spain the UNE 103-804-93 standard.

In general, as far as the regularization of the test is concerned, all Standards specify the technical requirements of the equipment, the method of execution of the field test and the presentation of results and minimum corrections that have to be considered when performing and interpreting a piezocone.

However, the current regulations do not refer to the methodology to be followed for the pre-drilling and/or re-drilling of the ground before a piezocone, which is sometimes necessary to allow the desired depths of investigation to be reached.

The pre-drilling and/or re-drilling of the ground and its subsequent covering by conventional drilling methods is a common practice due to the presence of high resistance materials that are not compatible with the CPTU test, due to the passage to more competent levels that can put the integrity of the equipment at risk, in order to free the rods themselves from the total friction accumulated in the tested section or to correct an abrupt deviation in the verticality of the test.

Nevertheless, the drilling of the ground before the execution of the CPTU generates a distortion with respect to the initial conditions of the materials to be tested and, in this sense, the different regulations in force do not contemplate a procedure that guides or regulates the way to proceed when this type of operation has to be carried out, neither the methodology to be followed to ensure the quality and validity of the results obtained, minimizing as far as possible the disturbance that this practice generates.

2. Objectives

During the in situ research campaign carried out in the area of the Llobregat river mouth (Barcelona, Spain), the results obtained from numerous onshore and offshore CPTU tests have been analyzed and a variation in the pore pressure data recorded in the onshore piezocones associated with the pre-drilling and/or re-drilling operations carried out to reach the objective test depths has been identified.

The pre-drilling and/or re-drilling operations that sometimes have to be performed on onshore CPTU tests are often associated with the injection of large flows of water at high pressures through the casing tubes that are used to stabilize the walls of the drilled cavity.

Consequently, this injection of water generates an increase in the hydraulic load for a period of time (variable depending on the permeability of the soil), which decreases as the excess interstitial pressure dissipates along the stratigraphic column of the soil to be tested.

This increase in piezometric height in turn generates a downward flow associated with a hydraulic gradient (i) that varies according to the permeability and total power of the different materials present in the study area.

In order to evaluate the degree of alteration that the pre-drilling and/or re-drilling operations generate in the stratigraphic column during the later execution of the CPTU tests, a total of 82 dissipation tests carried out onshore in granular materials have been analyzed to indirectly obtain the piezometric height at the moment when 100% dissipation is reached and thus evaluate the influence of the water flow generated according to the different lithologies crossed and its temporal evolution throughout the execution of the CPTU test.

In this case, based on the graphical representation of the different dissipation tests analyzed, the purpose is to evaluate the influence of pre-drilling and/or re-drilling according to the different lithologies penetrated and their evolution over the time between the end of the drilling operations and the execution of the CPTU tests.

The final objective of this research is to give visibility to an uncertainty found from the analysis of numerous CPTU tests carried out onshore and to evaluate the need for a standard methodology to be followed when carrying out piezocones that require pre-drilling and/or re-drilling of the ground to arrive at the required depths of investigation, while ensuring the validity of the data obtained and their representativity with respect to the ground tested.

3. Methodology

For this study, a total of 82 dissipation tests carried out during 26 onshore CPTUs in the area of the mouth of the Llobregat river have been analyzed.

The selected data correspond to dissipation tests carried out on granular materials since these, due to their high permeability, allow to indirectly determine the piezometric head at a point once the interstitial pressure increase has been completely dissipated, according to the following expression *(Terzaghi, K., 1936)*:

$$PL = DT - (9{,}81 \cdot Uh) \qquad (1)$$

Where PL is the Piezometric Level in meters, DT is the Dissipation Test Depth in meters and Uh is the Hydrostatic Pressure when the dissipation test arrives at the 100% of dissipation in Kilopascals.

In addition, the variation of the piezometric level generates a hydraulic gradient (i) that is associated with a flow of water from the zone of higher hydraulic load to the zone of lower load, which will be maintained over time until both piezometric levels are equalized and the resulting gradient approaches 0 (Fig. 1).

The flow associated with a hydraulic gradient can be defined according to the following expression *(Darcy, H., 1856)*:

$$Q = -K\frac{\Delta h}{\Delta L}A \qquad (2)$$

Where Q is the discharge, K is the permeability, $\Delta h/\Delta L$ is the hydraulic gradient and A is the stratigraphic level to study.

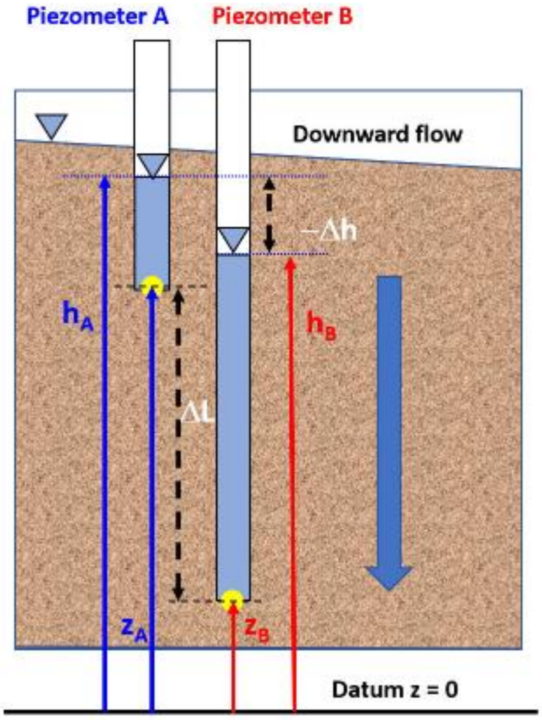

Figure 1. *Example of the factors needed to calculate a vertical gradient; in this case the flow potential is from the highest height (A) to the lowest (B) (William W. Woessner & Eileen P. Poeter, 2020).*

The hydraulic gradient has been calculated as a function of the interstitial pressure values (u) at the moment when the dissipation test can be considered as stabilized, which means that the total dissipation of the excess interstitial pressure of the considered hydraulic load has been reached.

In this case, the interstitial pressure measurements considered refer to piezocones where the sensor or porous stone is located at position u_2.

4. Results

The results obtained have been classified into 3 typologies according to the variations of the hydraulic load in the dissipation tests carried out at different depths (for the same CPTU test) and the time between them.

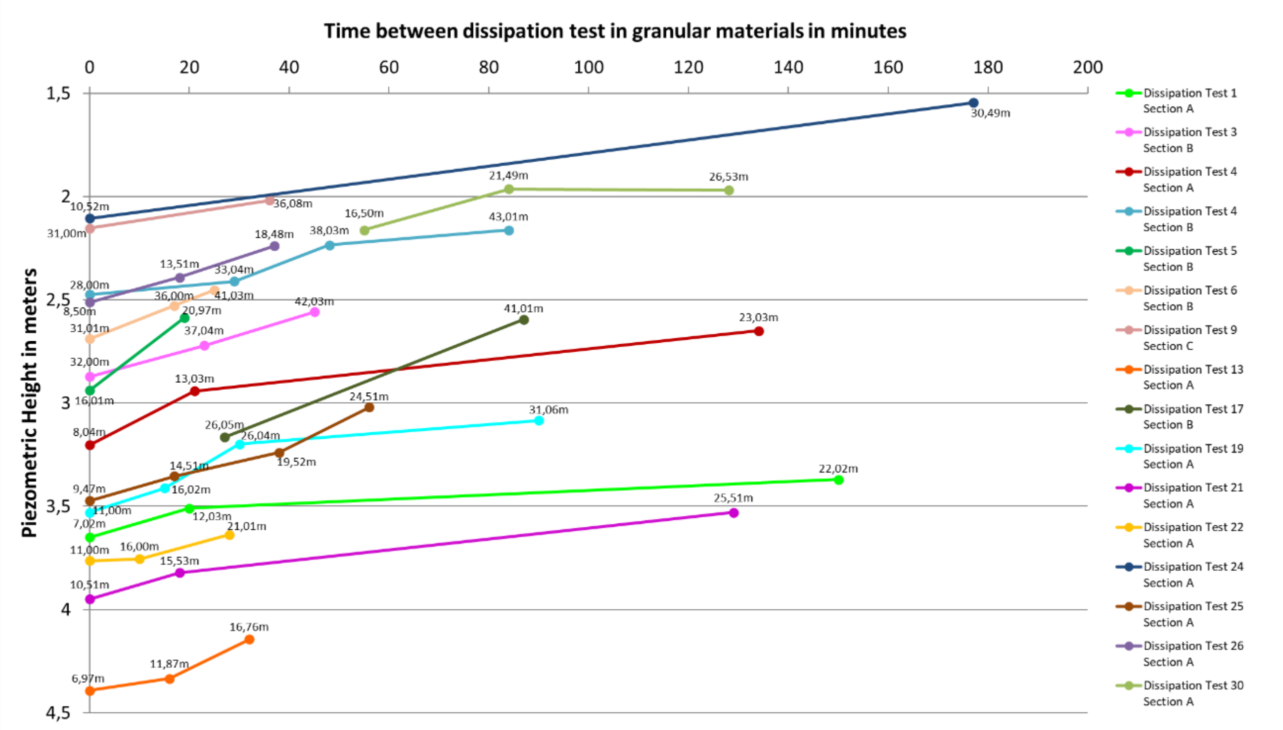

Figure 2. *Dissipation tests for Group I: Downward hydraulic loading as a function of time and depth.*

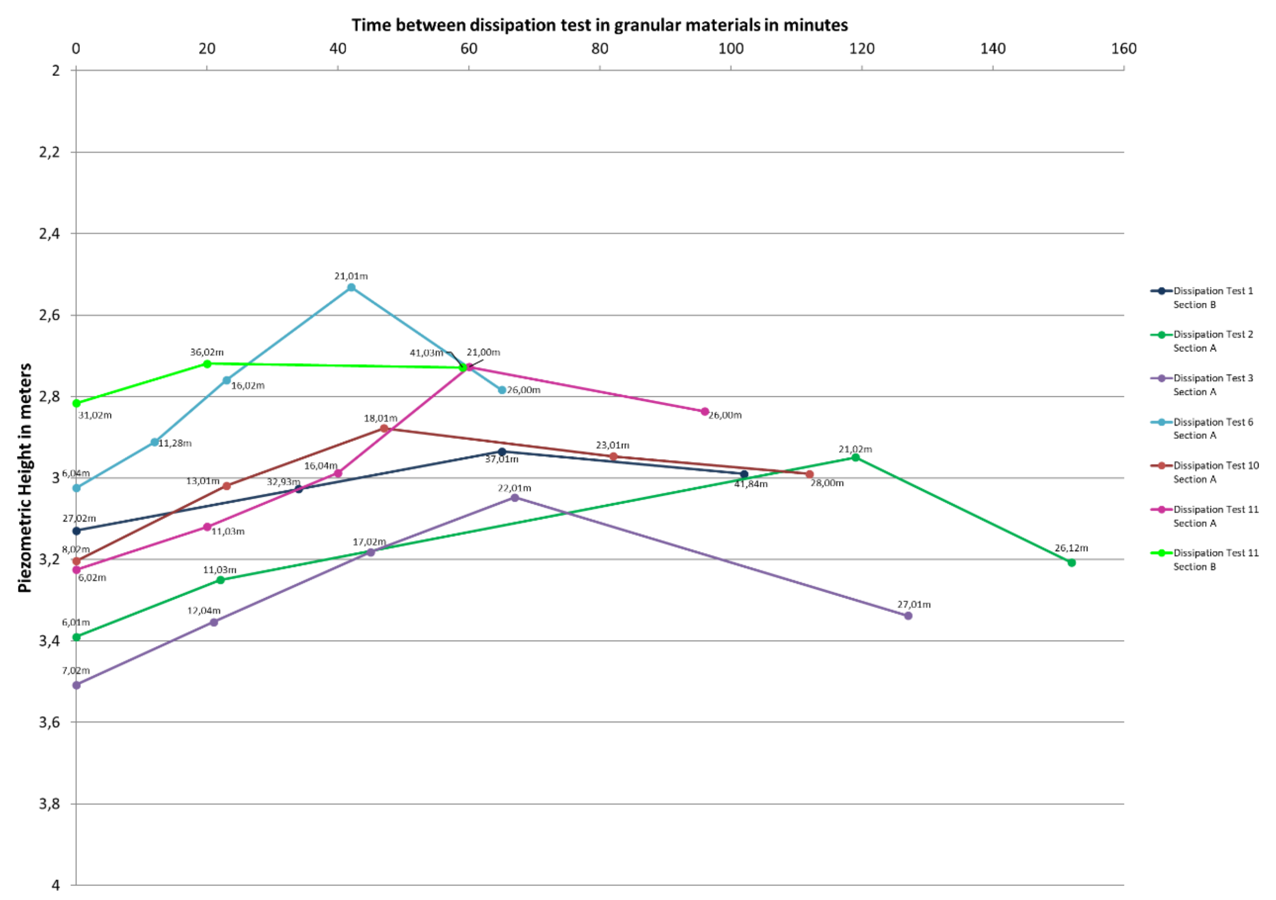

Figure 3. *Dissipation tests for Group II: Downward hydraulic loading and stabilization as a function of time and depth.*

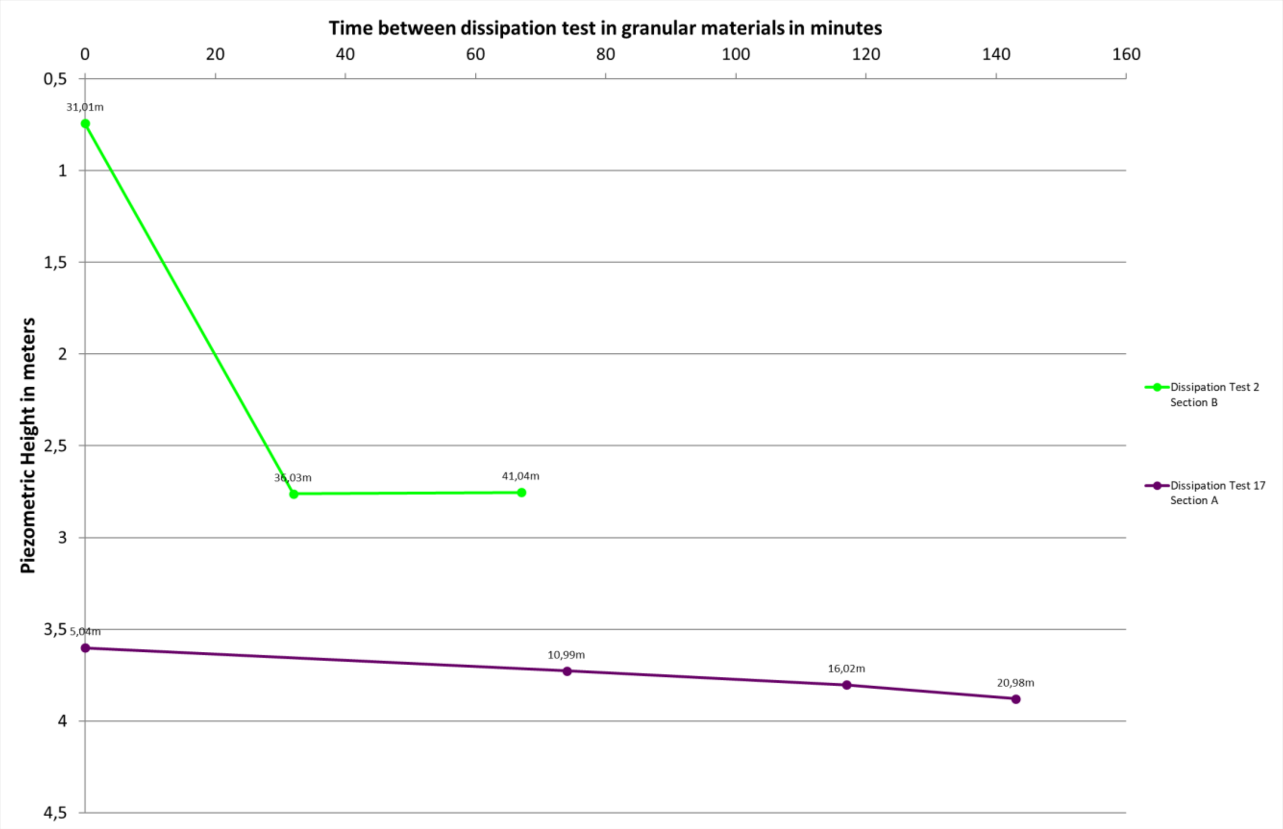

Figure 4. *Dissipation tests for Group III: Increasing hydraulic loading and stabilization as a function of time and depth.*

GROUP I: Downward hydraulic load as a function of time and depth

The graphic corresponding to the results obtained for Group I (Fig. 2) shows how the hydraulic load in the different dissipation tests analyzed decreases over time and depth. This dynamic indicates that, at the time of the dissipation test, there was a downward flow in the stratigraphic column that persisted during the execution of the CPTU test.

The hydraulic gradient values calculated for each dissipation test considered in Group I are presented in Table 1 below.

Table 1. *Hydraulic gradient calculated for every dissipation test considered in Group I.*

Dissipation Test	Dissipation Test Depth (m)	Piezometric Height (m)	Hydraulic Gradient
Dissipation Test 1 Section A	12,03 17,02 22,02	3,513 3,651 3,370	0,027 0,028
Dissipation Test 3 Section B	32,00 37,04 42,03	2,871 2,720 2,559	0,030 0,323
Dissipation Test 4 Section A	8,04 13,03 23,03	3,203 2,941 2,650	0,052 0,058
Dissipation Test 4 Section B	28,00 33,04 38,03 43,01	2,474 2,411 2,233 2,162	0,012 0,035 0,014
Dissipation Test 5 Section B	16,01 20,97	2,939 2,586	0,070
Dissipation Test 6 Section B	31,01 36,00 41,03	2,689 2,527 2,452	0,032 0,015
Dissipation Test 9 Section C	31,00 36,08	2,153 2,018	0,027
Dissipation Test 13 Section A	6,97 11,87 16,76	4,391 4,333 4,143	0,011 0,038
Dissipation Test 17 Section B	26,05 41,01	3,165 2,594	0,038
Dissipation Test 19 Section A	11,00 16,02 26,04 31,06	3,529 3,412 3,198 3,084	0,023 0,021 0,022
Dissipation Test 21 Section A	10,51 15,53 25,51	3,950 3,821 3,530	0,025 0,029
Dissipation Test 22 Section A	11,00 16,00 21,01	3,763 3,754 3,637	0,001 0,023
Dissipation Test 24 Section A	10,52 30,49	2,106 1,545	0,028
Dissipation Test 25 Section A	9,47 14,51 19,52 24,51	3,473 3,354 3,239 3,021	0,023 0,023 0,043
Dissipation Test 26 Section A	8,50 13,51 18,48	2,512 2,391 2,239	0,024 0,030

The most representative lithological type columns (according to the Robertson soil classification, 2010) corresponding to the CPTU tests considered in Group I are shown below (Fig. 5).

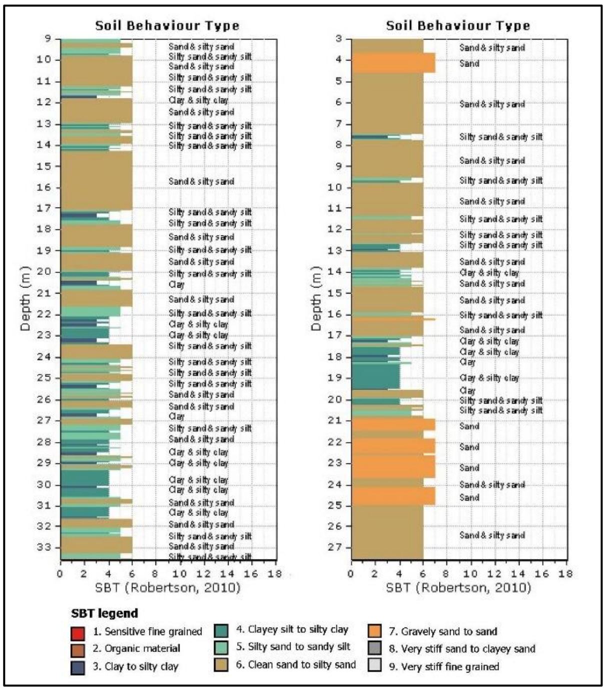

Figure 5. *Typical lithological columns most representative of the CPTU tests considered for Group I.*

In this case, and taking into account that most of the materials present in the CPTU tests correspond to mainly granular levels, the evolution of the different piezometric heights obtained from the analysis of the dissipation tests indicates that the piezocones executed after pre-drilling and/or re-drilling were carried out in conditions in which the water flow generated by these operations had not already dissipated and, therefore, the interstitial pressure values (u) recorded, both in the CPTU test itself and in the dissipation tests carried out, require corrections throughout the tested section to reduce this artificially generated increase in interstitial pressure.

GROUP II: Downward hydraulic load and stabilization as a function of time and depth

The graphic corresponding to the results obtained for Group II (Fig. 3) shows how the hydraulic load in the different dissipation tests performed decreases and then increases and/or stabilizes over time and depth. This dynamic indicates that, at the time of the dissipation test, there was a downward flow up to a certain depth and, after that, it tended to stabilize and/or disappear because of either the permeability of the materials involved in the increase of the hydrostatic load (so that the flow has not yet reached the lower levels during the execution of the CPTU test) or because of the complete dissipation of the increase in hydraulic load artificially generated by the pre-drilling and/or re-drilling of the ground.

The hydraulic gradient values calculated for each dissipation test considered in Group II are presented in Table 2 below.

Table 2. *Hydraulic gradient calculated for every dissipation test considered in Group II.*

Dissipation Test	Dissipation Test Depth (m)	Piezometric Height (m)	Hydraulic Gradient
Dissipation Test 1 Section B	27,02 32,93 37,01 41,84	3,129 3,027 2,935 2,990	0,020 0,022 **- 0,011**
Dissipation Test 2 Section A	6,01 11,03 21,02 26,12	3,339 3,250 2,949 3,207	0,017 0,030 **- 0,050**
Dissipation Test 3 Section A	7,02 12,04 17,02 22,01 27,01	3,508 3,353 3,181 3,047 3,338	0,030 0,034 0,026 **- 0,058**
Dissipation Test 6 Section A	6,04 11,28 16,02 21,01 26,00	3,024 2,911 2,759 2,532 2,783	0,021 0,032 0,045 **- 0,050**
Dissipation Test 10 Section A	8,02 13,01 18,01 23,01 28,00	3,203 3,019 2,878 2,947 2,990	0,036 0,028 **- 0,013** **- 0,008**
Dissipation Test 11 Section A	6,02 11,03 16,04 21,00 26,00	3,225 3,120 2,987 2,727 2,836	0,006 0,026 0,052 **- 0,021**
Dissipation Test 11 Section B	31,02 36,02 41,03	2,816 2,719 2,728	0,019 **- 0,001**

The negative hydraulic gradient (i) values obtained mainly in the dissipation tests performed at greater depths and, therefore, with more time having elapsed since the pre-drilling and/or re-drilling operation indicate the non-existence of water flow at these depths and/or its complete dissipation in the time between the dissipation tests considered.

The most representative lithological type columns (according to the Robertson soil classification, 2010) corresponding to the CPTU tests considered in Group II are shown below (Fig. 6).

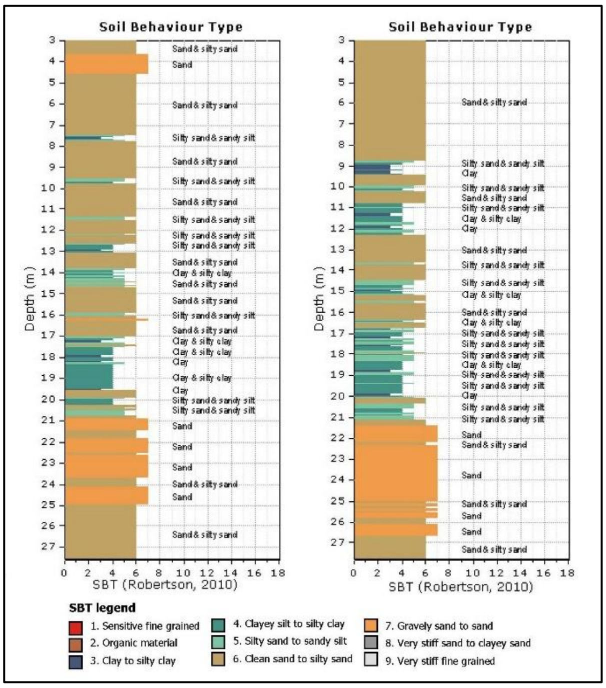

Figure 6. *Typical lithological columns most representative of the CPTU tests considered for Group II.*

In this case, and taking into account that most of the materials present in the CPTU tests considered correspond to granular materials with intercalations of cohesive levels (which present a much lower permeability), the evolution of the piezometric heights obtained from the analysis of the dissipation tests indicates that, during the execution of the piezocone tests, the initial hydraulic load conditions have been reached (prior to the pre-drilling and/or re-drilling operations) or that, due to the low permeability induced by the intercalated cohesive materials, the artificially generated hydraulic flow has not yet reached the lower levels tested.

GROUP III: Increasing hydraulic load and stabilization as a function of time and depth

The graphic corresponding to the results obtained for group III (Fig. 4) shows how the hydraulic load in the different dissipation tests carried out increases, in some cases stabilizing over time and depth. This dynamic indicates that, during the time elapsed between dissipation test and dissipation test analyzed within the execution of the same CPTU test, the increase in hydraulic load artificially generated by the injection of water during the pre-drilling and/or re-drilling of the ground has been completely dissipated.

The hydraulic gradient values calculated for each dissipation test considered in Group III are presented in Table 3 below.

Table 3. *Hydraulic gradient calculated for every dissipation test considered in group III.*

Dissipation Test	Dissipation Test Depth (m)	Piezometric Height (m)	Hydraulic Gradient
Dissipation Test 2 Section B	31,01	0,742	**- 0,401**
	36,03	2,761	0,001
	41,04	2,753	
Dissipation Test 17 Section A	5,94	3,601	**- 0,024**
	10,99	3,726	**- 0,015**
	16,02	3,803	**- 0,015**
	20,98	3,879	

The most representative lithological type columns (according to the Robertson soil classification, 2010) corresponding to the CPTU tests considered in Group III are shown below (Fig. 7).

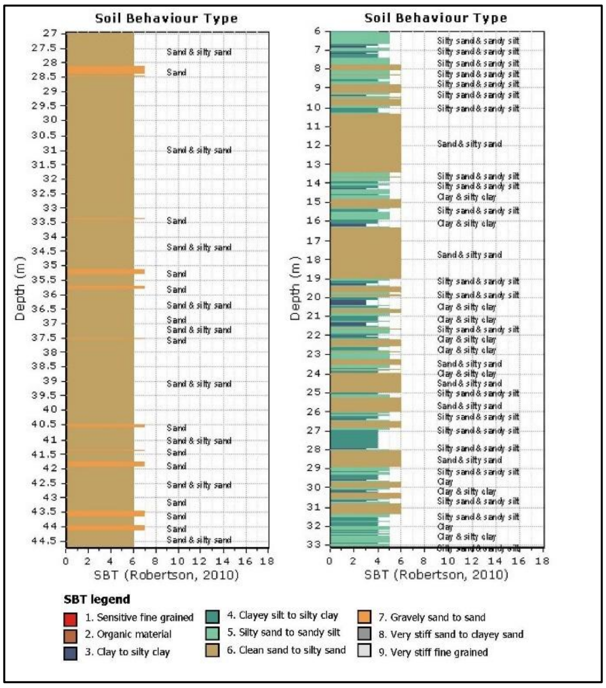

Figure 7. *Typical lithological columns most representative of the CPTU tests considered for Group III.*

In this case, and taking into account the lithological variability in the area where the CPTU tests were carried out (mainly granular areas and areas with abundant intercalations of cohesive materials), the evolution of the piezometric heights obtained from the analysis of the dissipation tests indicates that, during the execution of the piezocone tests, the initial hydraulic load conditions were reached, prior to the pre-drilling and/or re-drilling of the ground.

5. Conclusions

The execution of pre-drilling and/or re-drilling operations during the execution of piezocones, especially onshore, in order to reach the desired test depths, although it may be considered inadvisable, is a fairly common and operationally 'standard' procedure that is outside the various international regulations which currently govern the CPTU test.

When these drilling operations are carried out, a flow of water is introduced into the study area, which generates an increase in the hydrostatic load and, therefore, a flow of water associated with it that dissipates both vertically (according to the vertical permeability of each material, Kv) and horizontally (according to the horizontal permeability, Kh) along the entire lithological column to be analyzed.

Furthermore, the pore pressure data recorded during a dissipation test or the same pore pressure corresponding to the CPTU test itself executed after a pre-drilling operation and/or re-drilling of the ground, must be corrected in the subsequent analysis and interpretation according to the new situation.

In contrast, if these values are not corrected, the results obtained may not be representative of the soil tested, as it has been affected by an artificial water flow.

If we assume that the water flow generated in the test column due to the drilling and casing operations corresponds to a laminar flow (Re < 4 - 10), we can estimate the minimum time required to perform the CPTU test after pre-drilling and/or re-drilling by applying Darcy's law, thus avoiding obtaining anomalous data and the need to apply subsequent corrections to obtain representative values.

Even so, future research related to the effect of pre-drilling and/or re-drilling operations on pore pressure values and recorded dissipation tests is recommended so that, consequently, the different international regulations that define the execution of this type of in situ tests include a standardized procedure for carrying out these operations, as this is not currently regulated.

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