

DMT, CPTU and laboratory tests comparison for soil classification and strength parameters of deltaic soft soils in Barcelona Port

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ABSTRACT: An extensive geotechnical investigation was conducted on deltaic cohesive soft sediments of the Llobregat delta in a nearshore area of the Barcelona Port (Spain). Tests were carried out from a set of jack-up platforms in a sheltered area with water depths ranging between 8 and 20 m. This paper presents the results of the soil investigation focused on 8 triple points composed of Marchetti Dilatometer Tests (DMT), Cone Penetration Tests (CPTU) and rotary boreholes at the same location. The prediction of soil classification and strength properties based on well-known correlations from DMT and CPTU are compared to laboratory results on undisturbed samples recovered by Shelby tubes. Existing correlations are assessed for specific soft soils from Llobregat delta by evaluating their uncertainties.

Keywords: correlations, CPT, DMT, in situ tests, soil classification, strength

1. Introduction

The Llobregat delta has been extensively studied during the last twenty years due to the numerous infrastructures that have been developed in the south-western part of Barcelona. Among many others, the new terminal T1 at El Prat airport and the enlargement works for the construction of the South and East breakwaters provided numerous geotechnical data that have increased the knowledge of the quaternary sediments of the Llobregat delta. Moreover, due to its hydrogeological behaviour, the delta has been established as an important groundwater resource for Barcelona and surrounding cities. Therefore, detailed stratigraphic and tectonic studies have been of high importance for managing and protecting the aquifers from pollution and avoiding salt-water intrusions.

As part of its expansion strategy, the Port Authority of Barcelona promoted an intensive geotechnical campaign with the objective to fully characterize the seabed and deltaic quaternary soft soils for the design of three new quays and future new terminals and port facilities. The project area was located in the south part of the port, in a sheltered nearshore area with water depth ranging between 8 and 20 m. Investigated points were located from the north side of Muelle Prat along

the existing Moll de l'Energia, covering an area roughly of about 2500 x 220 m.

In order to keep to the tight schedule, field works were conducted from a set of two jack-ups working simultaneously during more than seven months



Figure 1. Field works were conducted from a set of two jack-ups working simultaneously during more than seven months

The geotechnical investigation comprised the following final scope:

1. 85 rotary boreholes with a rotary drilling rig, including 508 SPT tests and 412 thin wall undisturbed samples.

- Advanced in-situ tests: 103 CPTU with a 200 kN thrust capacity equipment and 11 DMT with tests every 0.5 m.
- An extensive laboratory test program.

The average investigation depth for boreholes and in-situ tests was 40 m. Among all field works, three locations were executed duplicating the tests (DMT+CPTU) and eight even triple (DMT+CPTU+Borehole), allowing results comparison. These tests were carried out through different moon-pools of the jack-up located at enough distance to avoid that soil disturbance could affect the rest of the tests. An overview of the survey area and the location of the eight triple points is shown in Fig.2.

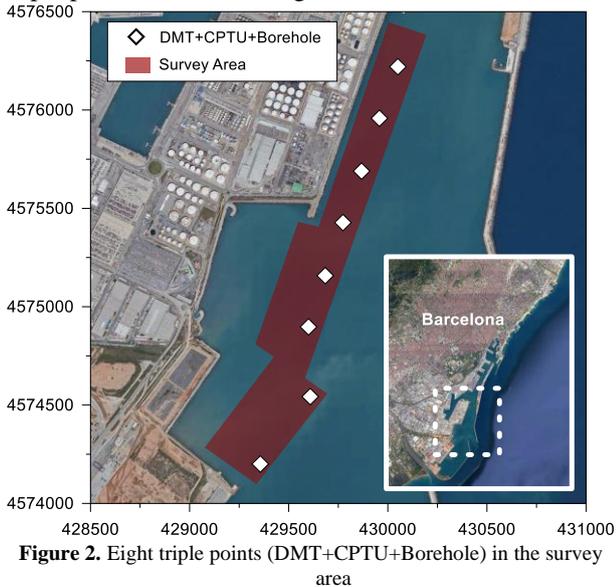


Figure 2. Eight triple points (DMT+CPTU+Borehole) in the survey area

This paper is focused on the results obtained in the eight triple points. The soil classification and strength parameters based on well-known existing correlations between DMT and CPTU are compared to laboratory results. The uncertainties of these correlations on soft soils from Llobregat delta are analysed.

2. Geological context

The regional tectonic context and the stratigraphic architecture of the Llobregat deltaic system has been extensively studied by many authors such as [1-7]. Some onshore and offshore integrations and correlations have been proposed using boreholes data and seismic profiles [8-12]. The general stratigraphy of Llobregat delta is presented in an onshore-offshore cross section in Fig. 3 [9]. From a general point of view, from bottom to top the main units are:

- Basement: formed by blue Pliocene marls and Paleozoic shales.
- Lower Detrital Complex: Pleistocene conglomerates, gravels and sands changing laterally to sands, silts and clays toward the sea.
- Upper Deltaic Complex: a thin transgressive sand layer below the main Holocene prodelta deposit formed by clayey silts. The delta front is composed by sands and silts and the alluvial plain by silts and clays.

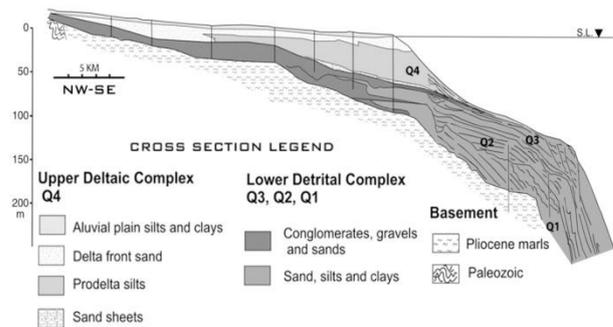


Figure 3. Geological onshore-offshore cross-section of the Llobregat delta. Adapted from [9]

3. Soft soils from Llobregat delta

The geotechnical behaviour of natural soils from Llobregat delta is well defined and has been subject of numerous publications, such as [13-18]. From a general point of view, investigated soils might be divided in two different geotechnical units:

- Silty fine to medium SAND with thin intercalations of clayey to sandy silt. These facies are interpreted as distal to proximal delta front in Fig.3.
- Clayey SILT variability interbedded with fine to very fine silty sands. These facies are interpreted as prodelta sediments in Fig.3.

A representative example of a CPTU is shown in Fig. 4. The two geotechnical units are plotted in the normalized SBT proposed by [19].

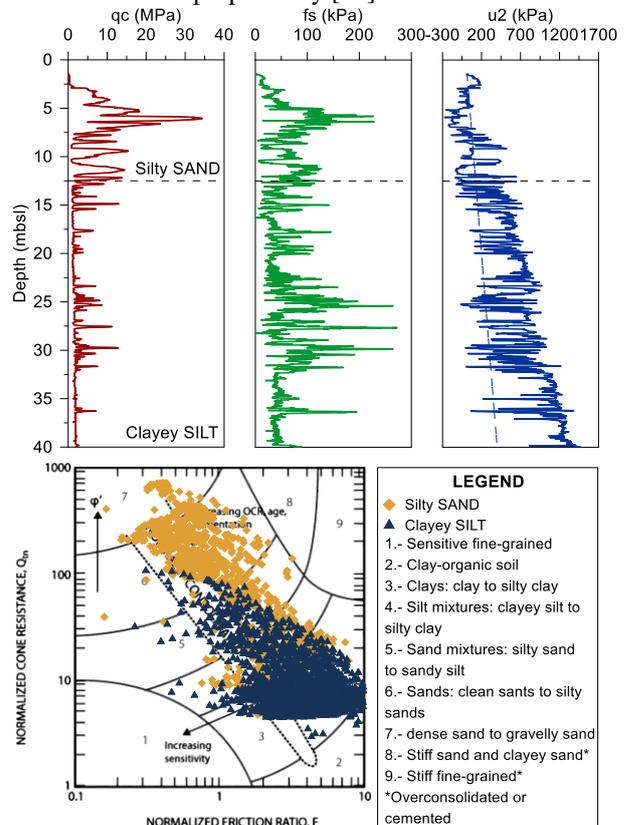


Figure 4. Example of CPTU in soft deltaic soils from Llobregat delta (above). The two geotechnical units plotted in the normalized Soil Behavior Type chart [19] (below)

No significant variations on soil conditions were observed throughout the survey area. The sand sheets layer from the Upper Deltaic Complex (Fig. 3) was located in largest tests below the clayey silt unit close to 50 m depth.

An extensive laboratory campaign was carried out on samples recovered during field works. Tests were defined with the aim on acquiring identification, classification, strength and deformational properties. An average value for some identification and classification tests on samples from the two main geotechnical units is shown in Table 1.

Table 1. Average values for identification and classification tests

Property	Silty SAND	Clayey SILT
Moisture (%)	25.95	29.84
Bulk Density (Mg/m ³)	1.96	1.95
LL (%)	24.98	32.53
PL (%)	17.70	21.31
Gravel content (%)	1.96	0.05
Sand content (%)	62.46	8.22
Silt content (%)	23.75	65.82
Clay content (%)	11.81	25.91

4. DMT, CPT and laboratory comparison

4.1. Preliminary discussion

Many authors have discussed about the goodness and limitations of to determine parameters by correlations from different tests. Since among the main objectives of a geotechnical survey is to provide the most accurate and reliable parameters for designers, the knowledge of the suitability of each particular test and the geotechnical parameters that are obtained is a key factor when defining the survey. The use of different techniques for determining soil behaviour seems to be appropriate but only when these techniques are correctly applied. In this sense, for instance, it is considered as the instrumental accuracy of CPT/CPTu and DMT is “laboratory-grade”, unlike “older” techniques such as the standard penetration test (SPT) [20].

It must be pointed out that the three techniques used for soil characterization in Llobregat delta provided data with different frequency in depth. Firstly, the primary parameters of the Cone Penetration Test (CPTU) (tip stress q_c , sleeve friction stress f_s , pore pressure u) were measured every 1cm. Therefore, around 32000 data for each primary parameter were available. Hence, it could be assumed as a continuous test. Secondly, the Flat Dilatometer (DMT) determines two readings (the lift-off or contact pressure p_0 and expansion pressure p_1) and it was carried out every 50cm so even the large number of tests (640 in the eight triple points). These tests ensured a suitable soil study, for the current work data was handled as non-continuous. Finally, laboratory tests were performed on selected sub-samples from undisturbed Shelby tubes recovered every 5m in each borehole. A total of 44 bulk density determinations were available. Thus, care is required when comparing these three different data sources. However no significant variations in soil conditions were observed along the

survey and for this reason the average value of each parameter from all data sources data was derived for comparisons. According to [21], comparison between individual values from nearby in situ test profiles at the same depth often show considerable scatter due to variations in soil stratigraphy and consistency. Any comparison between in situ tests should be done in terms of near continuous profiles with depth so that any variation in soil stratigraphy can be identified from the profiles.

The correlations used in this paper are based on an extensive database collected from different soils around the world. Nevertheless, they are approximate and will likely be influenced by variations in in situ stress state, soil density, stress history, age, cementation and soil sensitivity [21]. Assuming that each test type has advantages and limitations, this study is focused on assessing some of the most used existing correlations by evaluating their uncertainties for soft soils in Llobregat delta.

4.2. Unit weight

The soil unit weight in laboratory was determined following the specifications detailed in the UNE 103301:1994 standard. Results were compared with accepted estimations from direct DMT and CPTU measurements. The chart for estimating soil type and unit weight γ (normalized to the unit weight of water, γ_w) from DMT based on Material Index I_D and Dilatometer Modulus E_D was developed by [22]. Results are shown in Fig. 5.

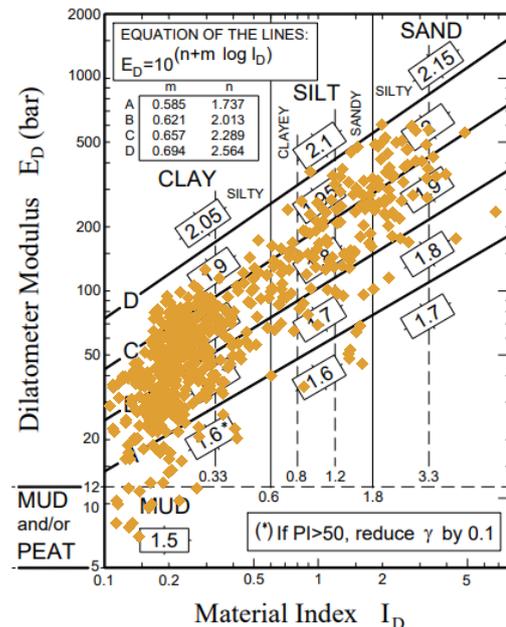


Figure 5. Soil type and unit weight in the chart proposed by [22].

The estimation of the unit weight from CPTU data has been studied by [23-27], among others. For this paper the equations proposed by [25-27] were used as it is assumed that are the most commonly used among the industry. Robertson & Cabal (2010) [25] proposed a chart to estimate the unit weight from direct measurements of CPTU, whose contours are approximated by Eq.1. Assuming a specific gravity (G_s) of 2.65 Mg/m³:

$$\gamma/\gamma_w = 0.27[\log F_r] + 0.36[\log (q_t/P_a)] + 1.236 \quad (1)$$

Where F_r is the friction ratio, q_t is the total cone resistance, and P_a is the atmospheric pressure. F_r and q_t are defined as follows:

$$F_r = [f_s/(q_t - \sigma_{v0})] \cdot 100 \quad (2)$$

$$q_t = q_c + u_2(1 - \alpha) \quad (3)$$

Where u_2 , σ_{v0} is the in situ total vertical stress the pore pressure measured directly behind the cone and α is the cone area ratio.

The unit weight from laboratory tests was compared with the average data from DMT predictive chart and with the correlation for CPTU data proposed by [25]. Results are shown in Fig. 6.

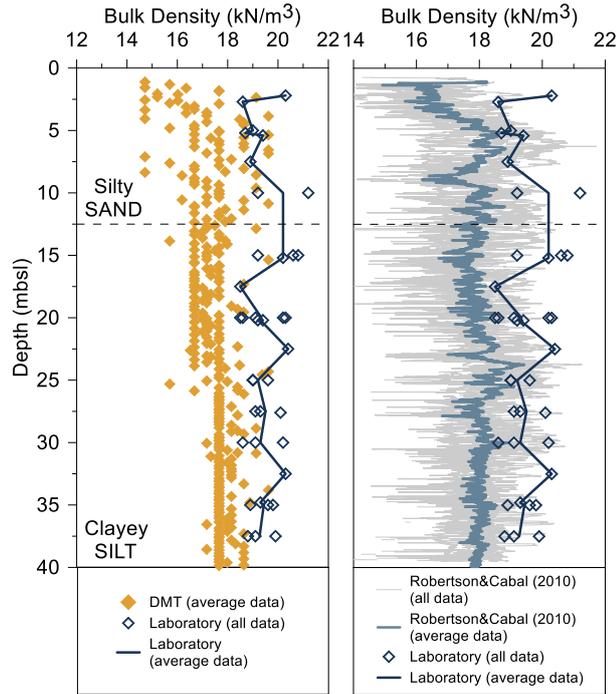


Figure 6. Comparison between the unit weight results from laboratory tests and predicted using the DMT measurements (left) and CPTU correlation proposed by [25] (right).

Mayne et al. (2010) [26] proposed an equation based on sleeve friction and effective overburden stress, since it became apparent that sleeve friction and σ'_{v0} alone sufficed to produce reasonable estimates of unit weight, thereby not requiring a reliance on q_t or u_2 readings. The resulting expression is detailed in Eq.4:

$$\gamma = 1.95\gamma_w(\sigma'_{v0}/\sigma_{atm})^{0.06}(f_s/\sigma_{atm})^{0.06} \quad (4)$$

Equation 4 showed a good correlation with a wide variety of materials including clays, silts, sands, tills and mixed soil types, but did not seem valid for diatomaceous clays and limited applicability on highly calcareous soils.

Mayne (2014) [27] proposed a direct relationship between the unit weight and the sleeve friction based on a large database of various soil types. The proposed expression is detailed in Eq. 5:

$$\gamma = 26 - 14/(1 + [0.5 \log(f_s + 1)]^2) \quad (5)$$

While it is well-known that the sleeve friction is perhaps the weakest in reliability of the three piezocone readings, in such a relationship the unit weight is increasing by a factor of two ($11.5 \text{ kN/m}^3 \leq \gamma \leq 23 \text{ kN/m}^3$) while the sleeve friction is spanning three orders of magnitude ($1 \text{ kPa} \leq f_s \leq 1000 \text{ kPa}$), thus an accurate f_s is not necessary given that the expected variance is on

the order of $\pm 1.5 \text{ kN/m}^3$ in the estimated value of unit weight [27].

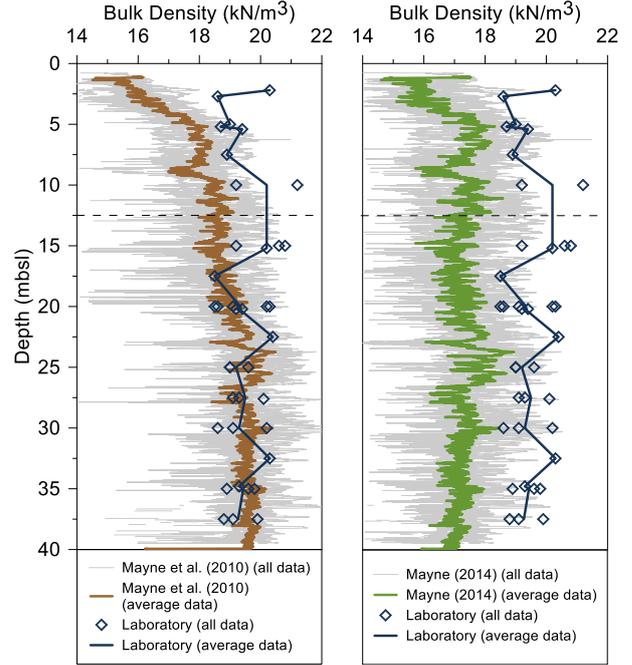


Figure 7. Comparison between the unit weight results from laboratory tests and predicted CPTU correlations proposed by [26] left and [27] right.

The unit weight estimated by the DMT chart provided results significantly lower than laboratory results. Data is scattered in the silty sand unit, probably due to its heterogeneity and the numerous thin cohesive layers interbedded. In the clayey silt unit, data shows a slight increment with depth. Generally, unit weight from DMT ranged between 16 and 18.5 kN/m^3 , whereas laboratory results could be assumed as a constant value of 19.5 kN/m^3 . Nevertheless, as indicated by [28], the main scope of the chart was not the accurate estimation of γ , but the possibility of constructing an approximate profile of σ'_{v0} , needed in the elaboration.

The unit weight from CPTU tests provided better results. The average values for the estimation proposed by [25] were around 1.5 kN/m^3 lower than the average laboratory data. Despite this difference, it must be pointed out that the profile was rather similar in both types of soils. This equation only takes into account primary parameters of the test, which is assumed as an advantage. Furthermore, whereas the equation proposed by [26] did not fit in with the laboratory data in silty sands, results were very consistent in the clayey silt unit. Nevertheless to use effective overburden pressure as an independent variable, which depends on the total weight, seems one of the inherent disadvantages of this model when the direct interpretation is considered [29]. In this sense, although the updated relationship between unit weight and CPTU data proposed by [27] does not take into account the overburden pressure, results seems not to fit particularly well neither the silty sands nor the clayey silts in the Llobregat soils. The predicted data is about 2.5 kN/m^3 lower than the laboratory data. It should be finally noted that the possible soil compression and disturbance during sampling with Shelby tubes was not taken into account for these comparisons.

4.3. DMT Parameters: ID, KD, ED

The following correlations were tentatively established by considering the three “intermediate” DMT parameters: material index I_D , horizontal stress index K_D and dilatometer modulus E_D [20, 30]:

$$I_D = (p_1 - p_0)/(p_0 - u_0) \quad (6)$$

According to [30], the soil type can be identified:

- Clay $0.1 < I_D < 0.6$
- Silt $0.6 < I_D < 1.8$
- Sands $1.8 < I_D < 10$

$$K_D = (p_0 - u_0)/\sigma'_{v0} \quad (7)$$

For normally consolidated clays (no aging, structure, cementation) the value of the horizontal stress index is around 2 [28]. The K_D profile is similar in shape to the Over Consolidation Ratio (OCR) profile, hence generally helpful for “understanding” the soil deposit and its stress history [30]. There is evidence that K_D increases slightly as soil sensitivity increases due to the higher pore pressures generated around the DMT probe during penetration [31].

$$E_D = 34.7(p_1 - p_0) \quad (8)$$

Where p_0 is the corrected first DMT pressure reading, p_1 is the corrected second DMT pressure reading, u_0 is the pre-insertion in situ equilibrium water pressure and σ'_{v0} is the in situ effective vertical stress.

These parameters from DMT were compared with correlations based on CPTU data. Robertson (2009) [21] suggested some correlations between normalized parameters of the CPTU and DMT. These correlations can be summarized as follows:

$$I_D = 10^{(1.67 - 0.67I_c)} \quad (9)$$

$$K_D = \beta(Q_t)^{0.95} + 1.05 \text{ when } I_c > 2.60 \quad (10a)$$

Where the constant β increases with soil sensitivity from 0.2 to 0.7. A value of 0.3 is suggested for insensitive fine-grained soils.

$$K_D = 0.144Q_t/10^{(1.67 - 0.67I_c)} \text{ when } I_c < 2.60 \quad (10b)$$

$$E_D/\sigma'_{v0} = 5Q_t \quad (11)$$

Where I_c is the Soil Behavior type Index [32] and Q_t is the normalized cone resistance, which are defined as follows:

$$I_c = [(3.47 - \log Q_t)^2 + (\log F_r + 1.22)^2]^{0.5} \quad (12)$$

The I_c index can be used to represent the boundaries between different soil types, where [32]:

- Gravelly sand to dense sand: $I_c < 1.31$
- Sands: $1.31 < I_c < 2.05$
- Sand mixtures: $2.05 < I_c < 2.60$
- Silt mixtures: $2.60 < I_c < 2.95$
- Clays: $2.95 < I_c < 3.60$
- Organic soils: $I_c > 3.60$

$$Q_t = (q_t - \sigma_{v0})/\sigma'_{v0} \quad (13)$$

The three “intermediate” DMT parameters calculated by direct DMT measurements and the estimation based on the correlations from CPTU measurements proposed by [21] are shown in Fig. 8, Fig. 9 and Fig. 10. In order to be able to do the comparison, all data has been included in graphs in a light colour together with the average value in a more marked colour for making visual the difference.

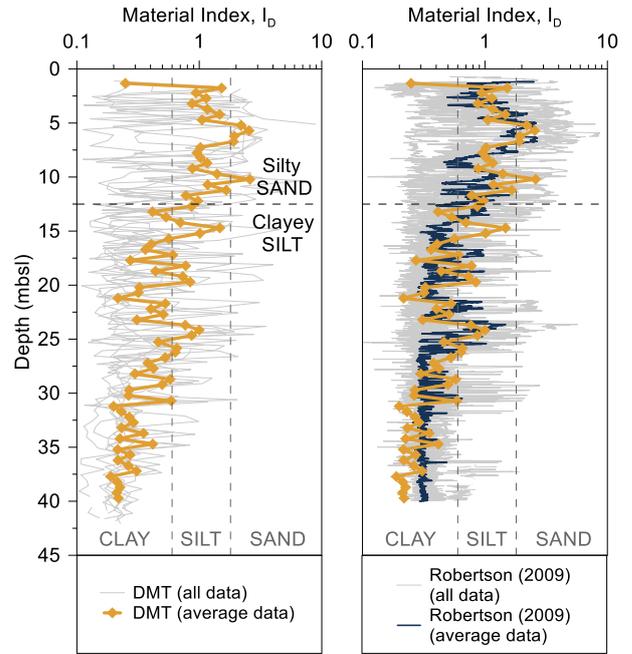


Figure 8. Comparison between the material index calculated by DMT measurements (left) and predicted using the DMT-CPTU correlation (right) proposed by [21].

As a general point of view, the measured DMT parameters and those predicted from the CPTU data using the equations proposed by [21] show a good correlation both in the silty sand and in the clayey silt level.

The comparison between the average I_D predicted by CPTU and the average calculated by direct DMT data is satisfactory. According to [30], the difference between the soil classification based on I_D and the grain size distribution from laboratory results would be associated at the I_D is a parameter reflecting the mechanical behaviour of the soil and not a soil classification based on grain size distribution or plasticity.

The value $I_c=2.60$ roughly corresponding to $I_D=1$ based on Eq. 6, is assumed as an approximate boundary between sand-like and clay-like (sandy silt to silty clay), according to [32]. In a general sense, CPT and DMT results are drained in sand-like soils and undrained in clay-like soil [20].

The horizontal stress index is strongly related to stress history. In this sense, [33] indicates that the big difference between CPT and DMT is that DMT provides the parameter K_D related to stress history whereas q_c is unaccompanied by a similar parameter containing information about stress history. The higher sensitivity of K_D to stress history plays an important role when CPT or CPTu and DMT parameters are used in combination (nor as alternative), e.g. for estimating OCR in sand or for liquefaction assessment, according to a most effective in-situ multi-parameter/multi-test approach [20]. For the current study, the constant β in Eq. 10a was adjusted to 0.5 in order to fit the K_D profile for both the measured by DMT and the predicted by CPTU values. Results are significantly good, especially in the clayey silt unit. In contrast, the dilatometer modulus predicted from CPTU data shows a very good correlation with the one calculated by DMT. The rapid

and large variations of E_D due to the soil heterogeneity are well captured.

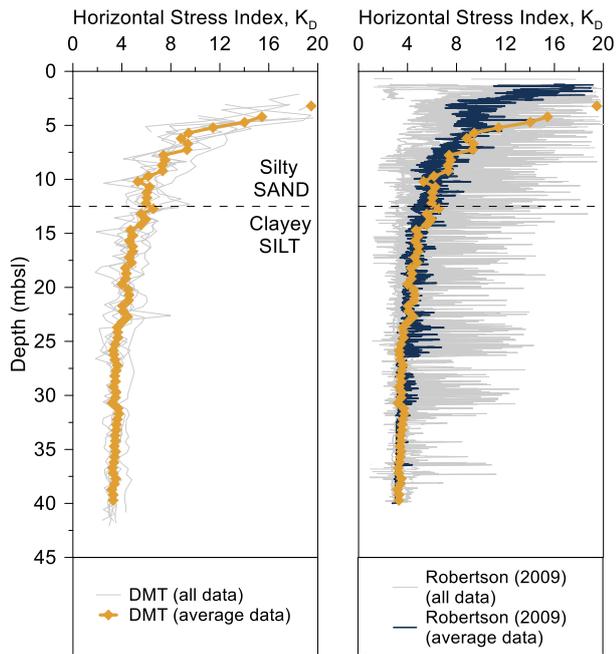


Figure 9. Comparison between horizontal stress index calculated by DMT measurements (left) and predicted using the DMT-CPTU correlation (right) proposed by [21] ($\beta=0.5$).

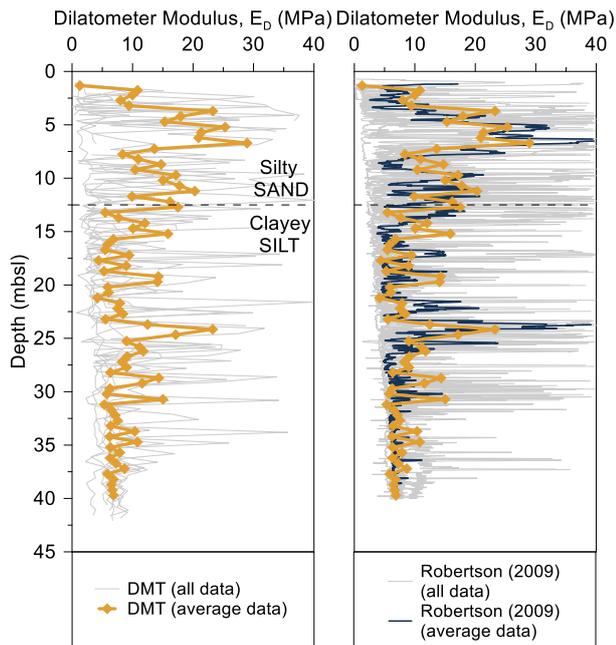


Figure 10. Comparison between the dilatometer modulus calculated by DMT measurements (left) and values predicted using the DMT-CPTU correlation (right) proposed by [21].

4.4. Net Cone Resistance q_{net}

Ouyang & Mayne (2017) [34] studied the relationship between the net cone resistance q_{net} measured in the CPTU and the p_1 , p_2 measured in a DMT test in soft clays. The relationship proposed by [34] is based on an assumed spherical cavity expansion mechanism for both devices, and supported by field measurements at 27 clay sites. The q_{net} is defined as:

$$q_{net} = q_t - \sigma_{v0} \quad (14)$$

The link between the DMT pressure readings p_0 , p_1 and q_{net} is defined as follows:

$$q_{net} = 2.93p_1 - 1.93p_0 - u_0 \quad (15)$$

The average net cone resistance directly measured by CPTU was compared with the predicted by DMT using Eq. 15. Results are shown in Fig. 11.

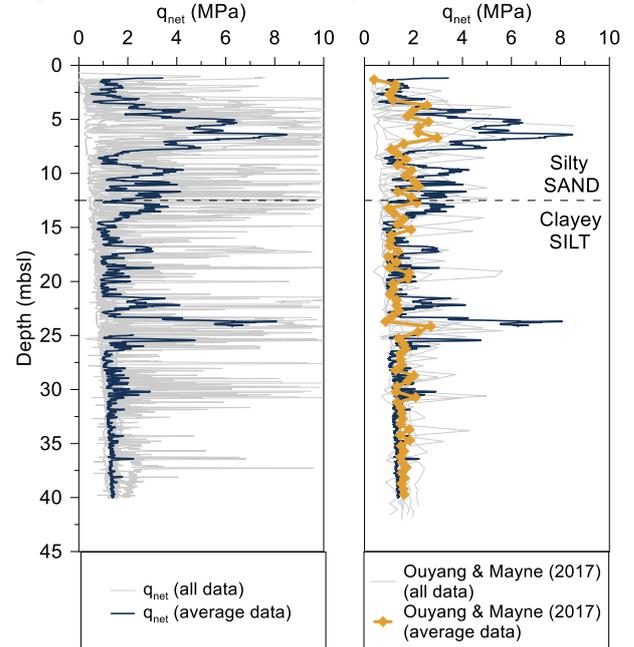


Figure 11. Comparison between the net cone resistance measured by CPTU and predicted using the CPTU-DMT relation by [32].

The two average profiles are in a good agreement, especially in the clayey silt unit. The predicted q_{net} from DMT measurements seems it is not enough sensitive to sudden increases on net cone resistance in sandy layers.

5. Conclusions

The comparison between DMT, CPTU and laboratory results in eight triple points from a nearshore geotechnical survey in deltaic soft soils from Llobregat river (Barcelona, Spain) provide satisfactory results.

According to [21], comparison between individual values from nearby in situ test profiles at the same depth often show considerable scatter due to variations in soil stratigraphy and consistency. Any comparison between in situ tests should be done in terms of near continuous profiles with depth so that any variation in soil stratigraphy can be identified from the profiles.

The DMT results and the correlations based on CPTU measurements proposed by [25-27] were analysed for soil unit weight determination. Although all results showed a similar trend, the correlation proposed by [26] provide significantly better results, essentially in the clayey silt unit. Furthermore, the average values for the correlation proposed by [25] were around 1.5 kN/m^3 lower than the average laboratory data. This difference keeps constant for both types of soils.

The measured DMT parameters (I_D , K_D , E_D) and those predicted from the CPTU data using the equations proposed by [21] show a good correlation both in the silty sand and in the clayey silt level. The rapid and

large variations in these parameters due to the soil heterogeneity are well captured.

Finally, the net cone resistance q_{net} from CPTU and the predicted from DMT measurements by [34] are in a good agreement, especially in the clayey silt unit. This proposal seems to be not enough sensitive to sudden increases on net cone resistance in sandy layers.

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