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Dynamic characteristics of the soils by Cone Penetration Tests (CPT)

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ABSTRACT: A geotechnical project requires a site-specific investigation to collect data regarding the subsurface conditions. Soil explorations must be made to determine the presence and identification of underlying strata, groundwater conditions, types of geomaterials, their depths and thicknesses, and the associated engineering parameters required for geotechnical design. The Cone Penetration Test (CPT) represents one of the most widely used on-site investigation methods in geotechnical engineering. This paper presents some empirical correlations available by Cone Penetration Tests (CPT) for determining the main geotechnical characteristics of soils. Moreover it aims to evaluate the small strain shear modulus by means of empirical correlations based on penetration tests results, CPT, Standard Penetration Tests (SPT) and Flat Dilatometer Marchetti Tests (DMT) or laboratory geotechnical investigations. It is aimed to achieve a better understanding of the obtained geotechnical parameters and the empirical correlations, justifying the investigation effort and enabling reliable input data for advanced dynamic analysis.

1 INTRODUCTION

Currently, CPT static sounding is one of the most popular field study as its specificity provides rich quasi-continuous data at depth. The CPT results enable to infer the soil profile as well as strength and stiffness parameters even at great depths in a cost effective way (Robertson et al., 1986, Kulhawy & Mayne, 1990; Fellenius & Eslami, 2000; Powell & Lunne, 2005; Robertson, 2009; Mayne, 2020).

The results presented in the article add new data to the documented knowledge. The results of field studies and guidelines on the soil of Noto area have been described in previous publications (Cavallaro et al., 2003a, 2003b; Cavallaro & Maugeri, 2003), and the data from soundings are the basis for determining soil parameters (Mayne, 2016) and engineering calculations.

In the light of the above, linking the numerical results of CPT static sounding to the genesis of soil will bring significant benefits to geotechnicians and engineering geologists in terms of data interpretation.

This paper intends to propose a critical evaluation of geotechnical parameters (Cavallaro, 2020) with special attention for small strain shear modulus G_o.

2 INVESTIGATION PROGRAM AND BASIC SOIL PROPERTIES

The Pliocene Noto deposits of Trubi Formation mainly consist of a medium stiff, over-consolidated lightly cemented silty-clayey-sand (Cavallaro et al., 2003a; Cavallaro & Maugeri, 2003).

The pre-consolidation pressure σ'_p and the over-consolidation ratio OCR $=\sigma'_p/\sigma'_{vo}$ were evaluated from the 24h compression curves of incremental loading (IL) oedometer tests.

Moreover, Marchetti's flat dilatometer tests (DMT) were used to assess OCR and the coefficient of earth pressure at rest K_o following the procedure suggested by (Marchetti, 1980).

For depths of about 15 m, DMT results show an OCR from 1 to 4.5 ($K_o = 0.5 \div 1.0$).

The OCR values inferred from oedometer tests (OCR from 1 to 3) are lower than those obtained from in situ tests.

One possible explanation of these differences could be that lower values of the pre-consolidation pressure σ'_p are obtained in the laboratory because of sample disturbance.

The value of the natural moisture content w_n prevalently range from between 12 - 37 %. Characteristic values for the Atterberg limits are: w_l = 37 - 69 % and w_p = 17 - 22 %, with a plasticity index of PI = 15 - 47 %. The obtained data indicate a low degree of homogeneity with depth of the deposits (Cavallaro et al., 2003b; Cavallaro & Maugeri, 2003).

Shear modulus G and damping ratio D of Noto soil were obtained also in the laboratory by resonant column tests (RCT). These tests were performed on Shelby tube specimens retrieved from Noto site. The Resonant Column/Torsional shear apparatus were used for this purpose.

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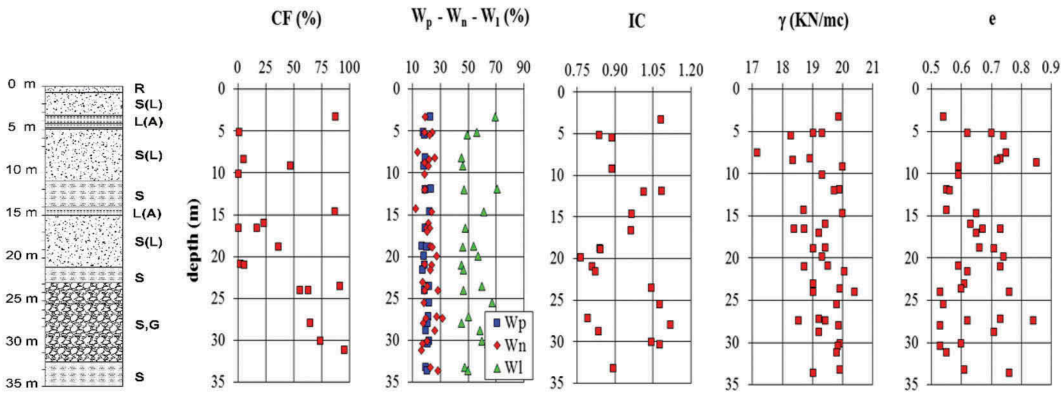

Figure 1. Borehole and index properties of Noto soil; where R: Landfill; S(L): Silty Sand; L(A): Clayey silt; S: Sand; S,G: Sand and Gravel.

3 EVALUATION GEOTECHNICAL PARAMETERS FROM CPT

CPT tests are widely used to investigate the subsoil in order to obtain information on the different physical-mechanical properties of the soils. Empirical laws are therefore available for determining the main geotechnical characteristics of soils.

The following geotechnical parameters have been determined:

- Total unit weight γ;
- Angle of shear resistance ϕ';
- Undrained resistance c_u;
- Shear modulus G_o.

It is possible to evaluate the total weight unit γ by empirical correlations of CPT in situ measurement:

- Mayne et al. (2010):

$$\gamma_t = 11.46 + 0.33\log(z) + 3.1\log(f_s) + 0.7\log(q_t) \quad (1)$$

where z = depth [m], f_s = sleeve friction resistance [kN/m^2] and q_t = corrected cone resistance [kN/m^2].

- Robertson & Cabal (2010):

$$\gamma/\gamma_w = 0.27\,[\log(R_f)] + 0.36\,[\log(q_t/P_a)] + 1.236 \quad (2)$$

where γ_w = water weight unit [kN/m^3], $R_f = (f_s/q_t)$ = friction ratio [-], q_t = corrected cone resistance [kN/m^2] and Pa = atmospheric pressure, expressed in the same unit of measurement of q_t.

- Mayne & Peuchen (2012):

$$\text{a) } \gamma_t = 26 - 14/[1 + 0.5\log(f_s+1)]^2 \quad (3)$$

$$\text{b) } \gamma_t = 12 + 1.5\ln(f_s+0.1) \quad (4)$$

for clays and sands.

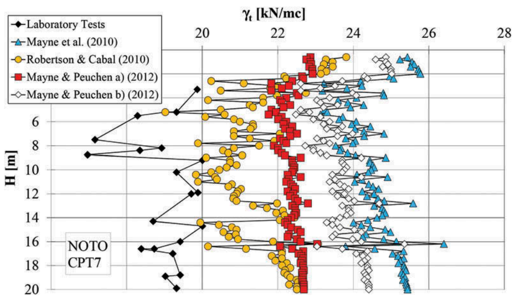

Figure 2. Total unit weight γ by empirical correlations based on CPT.

Figure 2 shows a comparison between the results obtained in the laboratory and those obtained by the empirical relationships proposed.

It is possible to observe that the results obtained are comparable even though the relationship proposed by Robertson & Cabal (2010) is better aligned with the experimental results.

Numerous empirical correlations have been proposed for the determination of ϕ':

- Meyerhof (1951):

$$\phi' = 17 + 4.49\ln(q_c) \quad (5)$$

where q_c = cone resistance [kg/cm^2].

- De Beer (1965):

$$\phi' = 5.9 + 4.76 \ln(q_c/\sigma'_{vo}) \quad (6)$$

where σ'_{VO} = effective vertical stress [kg/cm^2].

- Dourgunouglu & Mitchell (1975):

$$\phi' = 14.4 + 4.8\ln(q_c) - 4.5 \ln(\sigma'_{vo}) \quad (7)$$

the terms q_c and σ'_{vo} are expressed in the same unit of measurement [kg/cm^2].

- Robertson et al. (1983):

$$\tan\phi' = 1/2.68 [\log(q_c/\sigma'_{vo}) + 0.29] \quad (8)$$

the terms q_c and σ'_{vo} are expressed in the same unit of measurement [kPa].

- Kulhawy & Mayne (1990):

$$\phi' = 17.6 + 11 \log[q_c/(\sigma'_{vo} \cdot \sigma_{atm})] \quad (9)$$

where $\sigma_{atm} = p_a$ = atmospheric pressure, expressed in the same unit of measurement of q_c [kPa].

- Marchetti (1997):

$$\phi' = 28 + 14.6 \log(K_D) - 2.1 [\log(K_D)]^2 \quad (10)$$

where K_D = horizontal stress index by DMT ($q_c/\sigma'_{vo} \cong 33 \cdots K_D$).

- Jefferies & Been (2006):

$$\phi' = \phi_{cv} + 15.84[\log(Q_{tn})] - 26.88 \quad (11)$$

where ϕ_{cv} = constant volume friction angle and $Q_{tn} = (q_t - \sigma_{vo})/\sigma'_{vo}$ normalized cone resistance.

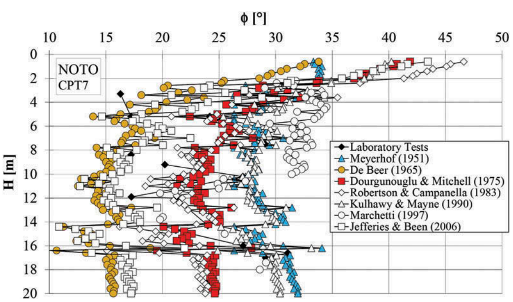

Figure 3. Angle of shear resistance ϕ' by empirical correlations based on CPT.

Regarding the results obtained for the angle of shear resistance ϕ', reported in Figure 3, it is observed that the values obtained in the laboratory by direct shear tests intersect all the empirical relationships proposed. Probably because these relations fail to, evaluate correctly the stratigraphic variations of the soil. High values of ϕ' were obtained in correspondence of the most superficial layers where no laboratory data is available. Overall, the Robertson & Campanella (1983) equation seems to approximate better the results of the direct shear tests.

As for the evaluation of the undrained resistance c_u the following empirical expressions were used:

- Lunne et al. (1976):

$$c_u = (q_c - \sigma_{vo})/(20.7 - 0.18 \text{ PI}) \quad (12)$$

where PI = plasticity index.

- Lunne & Kleven (1981) and Lunne at al. (1997):

$$c_u = (q_c - \sigma_{vo})/N_k \quad (13)$$

where N_k = empirical factor for bearing capacity dependent on depth and opening angle of the penetrometer cone (11 - 19).

Figure 4 shows the c_u values obtained by laboratory tests and empirical correlations. The laboratory data aligns well with the c_u values derived from the correlations. High values of undrained resistance were obtained by the expression of Lunne & Kleven (1981) on the surface layers and at a depth of about 16 m.

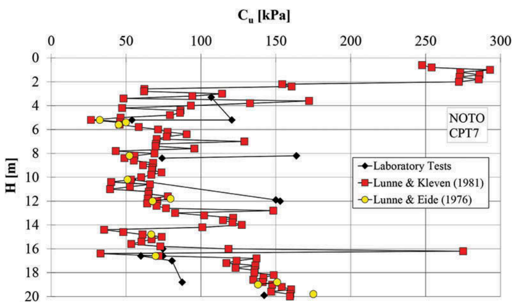

Figure 4. Undrained resistance c_u by empirical correlations based on CPT.

4 EVALUATION G_O FROM CPT

The small strain shear modulus G_o can be evaluated by laboratory Resonant Column Tests (RCT) (Capilleri et al., 2014; Castelli et al., 2016a) or in situ by Down Hole tests and SDMT (Castelli et al., 2016b; Cavallaro et al., 2012a, 2012b; Marchetti et al., 2008; Cavallaro

& Grasso, 2021) using the relationships: $G_o = \rho V_s^2$ (where: ρ = mass density) based on theory of elasticity.

An attempt was made to evaluate the small strain shear modulus by means of the following empirical correlations based on penetration tests results, CPT, SPT and DMT or laboratory results available in literature (Figure 5).

- Imai & Tomaichi (1990):

$$G_o = 28 \cdot (q_c)^{0.611} \tag{14}$$

for any soil.

- Mayne & Rix (1993):

$$G_o = \frac{406 \cdot q_c^{0.696}}{e^{1.13}} \tag{15}$$

for clayey strata;

where: G_o and q_c are both expressed in [kPa] and e is the void ratio. Equation (15) is applicable to clay deposits only.

- Simonini & Cola (2000):

$$G_o = 49.2 \cdot (q_t)^{0.51} \tag{16}$$

It is also possible to evaluate the small strain shear modulus using the relation $G_o = \rho \cdot V_s$ by the following equations proposed by Ohta & Goto (1978) and Yoshida and Motonori (1988) for the shear waves velocity V_s:

- Ohta & Goto (1978):

$$V_s = 69 \cdot N_{60}^{0.17} \cdot Z^{0.2} \cdot F_A \cdot F_G \tag{17}$$

where: V_s = shear wave velocity (m/s), N_{60} = number of blow/feet from SPT with an Energy Ratio of 60 %, Z = depth (m), F_G = geological factor (clays = 1.000, sands = 1.086), F_A = age factor (Holocene = 1.000, Pleistocene = 1.303)

- Yoshida and Motonori (1988):

$$V_s = \beta \cdot (N_{SPT})^{0.25} \cdot \sigma' vo^{0.14} \tag{18}$$

where: V_s = shear wave velocity (m/s), N_{SPT} = number of blows from SPT,σ'_{VO} =vertical pressure, β = geological factor (any soil=55, fine sand=49).

- Hryciw (1990):

$$G_o = \frac{530}{(\sigma'_v/p_a)^{0.25}} \frac{\gamma_D/\gamma_w - 1}{2.7 - \gamma_D/\gamma_w} K_o^{0.25} \cdot (\sigma' v \cdot p_a)^{0.5} \tag{19}$$

where: G_o, σ'_v and p_a are expressed in the same unit; p_a = 1 bar is a reference pressure; γ_D and K_o are respectively the unit weight and the coefficient of earth pressure at rest, as inferred from DMT results according to Marchetti (1980).

- Jamiolkowski et al. (1995):

$$G_o = \frac{600 \cdot \sigma_m^{'0.5} p_a^{0.5}}{e^{1.3}} \tag{20}$$

The Jamiolkowski et al. (1995) method was applied considering a given profile of void ratio.

The values for parameters, which appear in equation (20), are equal to the average values resulting from laboratory tests performed on quaternary Italian clays and reconstituted sands.

Equation (20) incorporates a term, which expresses the void ratio; the coefficient of earth pressure at rest only appears in equation (19). However only equation (19) tries to obtain all the input data from the DMT results.

As regard Noto soil the G_o values obtained with the methods above indicated for CPT and SPT are plotted against depth in Figure 5.

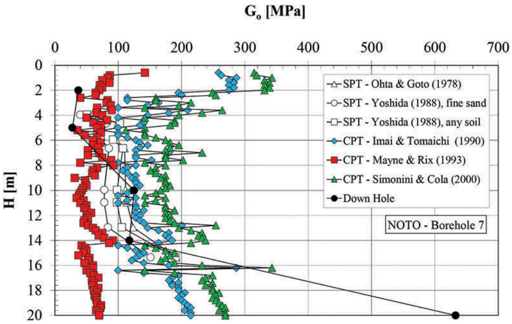

Figure 5. Small strain shear modulus G_o by empirical correlations based on CPT and SPT.

The results obtained show a greater similarity between the G_o results obtained by the empirical correlations proposed for SPT, which, moreover, are quite close together. The G_o values, obtained through the correlation equations proposed for CPT are more dispersed and higher.

The lowest values of the shear modulus are obtained by the equation proposed by Mayne & Rix (1993). Only by the Down Hole test it is possible to identify the rapid increase of G_o at a depth of 20 m in correspondence with some layer characterized by higher mechanical characteristics that both CPT and SPT cannot identify.

The N_{60} values, experimentally determined during SPT, did not show any important variation in the transition zone at depth of 20 m, where the characteristics of the soil change from silty sand to sand and then to sand with gravel.

Standard Penetration Tests were performed at intervals from 1.5 to 3.0 m. The quite large interval used could explain why the thin sand layers were not detected. Consequently, the obtained G_o values, in the transition zone, resulted to be quite low.

Unfortunately, the depth investigated by DMT is not able to intercept the most consistent layers of sand and sand with gravel. However, the method by Hryciw (1990) is the best one to follow the trend of the results obtained from the Down Hole tests, as can be seen in Figure 6.

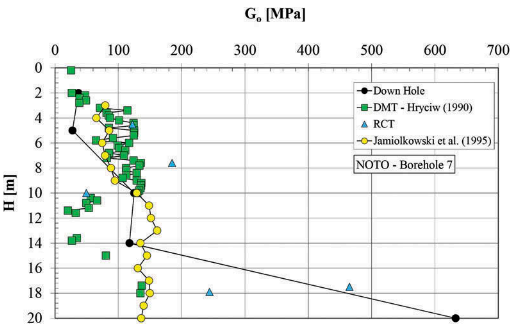

Figure 6. G_o from Down Hole, empirical correlation and RCT.

From a comparison between Figure 5 and Figure 6 all the considered methods show very different G_o values of the Pliocene Noto soil. On the whole, Down Hole seem to provide the most accurate trend of G_o with depth even if the available data are unable to investigate the behavior of the soil for depths greater than 20 m. The method by Jamiolkowski et al. (1995) was applied considering a given profile of void ratio but while guaranteeing continuity of results, it fails to intercept the most consistent layers of sand and sand with gravel.

In Figure 6 the RCT results are also reported. The data obtained also show as the dynamic laboratory tests are able to interpret the G_o trend obtained from the Down Hole test.

Figure 7 reports a comparison between DH test measurements and the corresponding empirical correlations. Since the DH test was performed with an interval of about 5 m, it was necessary to interpolate the intermediate values. From the comparison obtained it is possible to observe a more disordered initial phase in correspondence with the more superficial layers while subsequently a horizontal linear relationship is highlighted with the exception of the depth of 16.20 m.

5 CONCLUDING REMARKS

A site characterization for a possible advanced dynamic response analysis has been presented in this paper. On the basis of the data shown it is possible to draw the following conclusions:

- empirical correlations between the small strain shear modulus and penetration test results were used to infer G_o from SPT, CPT, DMT and Down Hole. This comparison clearly indicates that a certain relationship exists between G_o and the penetration test results, which would encourage to establish empirical correlations for a specific site. This approach makes it possible to consider the spatial variability of soil properties in a very cost effective way.
- The values of G_o were compared to those measured with DMT and DH tests. This comparison indicates that some agreement exists between empirical correlations by DMT and DH test.
- relationships like those proposed by Jamiolkowski et al. (1995) seem to be capable of predicting G_o profile with depth only in the initial strata. The accuracy of these relationships could obviously be improved if the parameters, which appear in the equations, were experimentally determined in the laboratory for a specific site.
- Down Hole test only is probably able to investigate correctly the various layers of soil, identifying even the smallest variations in the mechanical characteristics.

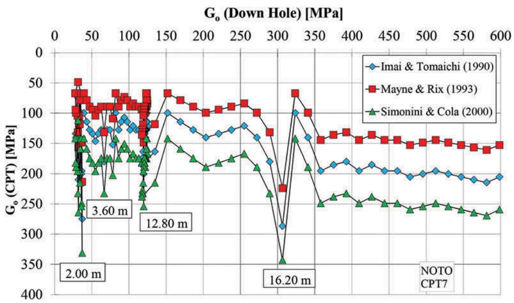

Figure 7. G_o from Down Hole vs G_o by empirical correlation.

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