Experiences acquired in the use of the seismic flat dilatometer (SDMT) and piezocone (CPTu) for an enhanced site characterization of Mexico City soft clay

Les enseignements tirés de l'utilisation de dilatomètre sismique (DMT) et piézocône (CPTu) pour une meilleure caractérisation du site dans l'argile molle au Mexico

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ABSTRACT: This paper shows the merits of using SDMT and CPTu that do meet international standards and the advantages of additional CPTu parameters such as friction (f_s), pore pressure (u_2) and inclinometers for quality control of the data for Mexico City clay deposits, which are very soft soils with high plasticity index ($100<IP<500$) and voids ratio ($5<e<11$). In addition, the supplementary information obtained by using them in combination for an enhanced site characterization sites are discussed. Field measurements indicate that V_s profiles obtained with the SDMT are very similar to those obtained with geophysical methods. Also, the results from laboratory tests on undisturbed samples and shear vane test VST were to assess available correlations to SDMT and CPTu data for indirect estimation of geotechnical parameters, and selection of appropriate correlations for Mexico soft clay deposits.

RÉSUMÉ : Ce travail montre les avantages de l'utilisation des essais sur le terrain SDMT et CPTu pour la caractérisation des sols mous dans Mexique. Mesures sur le terrain indiquent que les profils de vitesse obtenus avec SDMT sont très similaires à ceux obtenus avec des méthodes puits géophysiques. Lorsque l'on compare les résultats de SDMT et CPTu dosant avec les résultats des tests de laboratoire et VST, les équations ont été proposées pour estimer de façon empirique les paramètres mécaniques des sols mous du Mexique.

KEYWORDS: Soft soil, *in situ* tests, piezocone, dilatometer, vane shear test, correlations, shear wave velocity, Mexico City clays.

1. INTRODUCTION

Field tests, such as the Vane Shear Test (VST), Piezocone (CPTu) and the Seismic Flat Dilatometer (SDMT), and the correlations between the results of the field tests and the mechanical properties of soils are useful tools that complement conventional geotechnical exploration and enrich the stratigraphic characterization of very soft soil deposits.

A frequent problem with conventional exploration methods, particularly in soft soils and without field testing, is the alteration induced in soil samples. In effect, due to the diversity of the factors that can alter the sample (*e. g.* the stress relaxing condition during sampling, the deformation induced when introducing and taking out the sampler or upon performing tooling on the sample, variations in natural humidity and temperature during sampling, transportation, storage, tooling and laboratory testing) the uncertainty in the values of mechanical properties is high. Even when different strategies exist to evaluate the quality of the sample (*e.g.* Lunne *et al.* 2006), the main problem is the cost and the time needed to ensure that unaltered samples are taken. In contrast, using field testing, as available today, it is possible to do testing and evaluate the quality of the information obtained on site.

From the point of view of dynamic characterization, there are also uncertainties: i) the method to be used to define the profile of the modulus of shear rigidity (G_{max}) and the damping (ξ_{min}) of small deformations; ii) the verticality of the casing in the case of borehole techniques; iii) the direction of wave propagation; iv) the type of wave observed; v) the level of the deformation induced and, vi) the knowledge and experience of the engineer that makes the interpretation and signal reduction. For example, with respect to commonly used techniques, there are some in which ground alteration is induced (down-hole, cross-hole, suspension logging, SL, seismic piezocone SCPTu and SDMT), and others where the level of alteration can be considered null (Spatial Autocorrelation Method, SPAC, Multichannel Analysis of Surface Waves, MASW), which makes it logical to expect that the results will differ when comparing techniques with or without subsoil alteration.

This paper shows the merits of using CPTu, SDMT and VST that meet international standards and the advantages of additional CPTu parameters such as friction (f_s), pore pressure (u_2) and inclinometers for quality control of the data for Mexico City clay deposits. Based on laboratory and *in situ* tests, three sites are being studied in Mexico in order to verify empirical relationships that exist between the results of the CPTu and SDMT testing and the mechanical properties of the clay deposits, especially the undrained resistance obtained with vane shear test (VST), the influence of stress and the degree of pre-consolidation (*OCR*). Finally, profiles of dynamic shear modulus using SDMT are compared with geophysical methods (SL, MASW and SPAC).

1.1 *Mexico City soft deposits characterization*

The soft clay deposits within the Mexico City are characterized by an high humidity ($100<w_n<900$), high plasticity index ($100<PI<500$), large one-dimensional compressibility ($C_{c,max}\simeq 10$) and low shear wave velocity (V_s<100m/s). Those unusual values are produced mainly by the clay microstructure and composition, and the high diatoms content (Rangel *et al.* 2014; Fig 1).

1.2 *Exploration campaign*

The exploration campaign consisted in obtaining unaltered samples, conventional laboratory testing and in performing the following exploration techniques: CPTu, SMDT, VST, SL, MASW and SPAC.

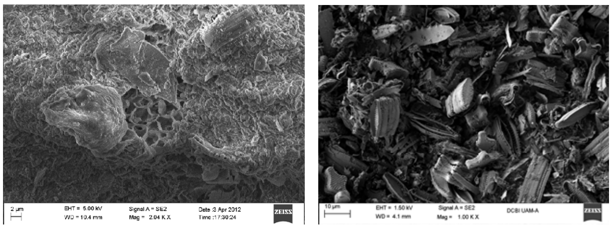

Figure 1. Images from the electron scanning microscope on Mexico City clay deposits (Rangel *et al*. 2014)

1.2.1 *Piezocone (CPTu)*

Currently Piezocones are digital and measure the resistance of the tip (q_c), the sleeve friction (f_s) and the excess pore pressure (u_2), as well as the inclination and the penetration velocity. In accordance with international standard ISO 22476-1:2012, the piezocone is driven at a constant velocity of 2cm/s.

The interpretation of results begins with correcting the value of tip resistance q_c due to excess pore pressure generated by the same drive, in the space of the instrument's filtering element. Once the corrected tip resistance q_T is determined, it is possible to define the stratigraphic profile, and later, by means of correlations, to determine the type of soil, s_u, the deformation modulus, in the short and long term, k_o, *OCR*, etc.

the role of the constant penetration speed of 2cm/s and of the inclination in piezocone are important. In effect, driving at a slower velocity than marked by the norm implies to obtain lower values of the tip resistance, while the contrary effect is seen at a greater velocity (Santoyo, 1989). On the other hand, severe vertical deviation causes measurements of virtual depths. Fig. 2 shows a typical probe of the area of a virgin lake to the depth of the first hard layer.

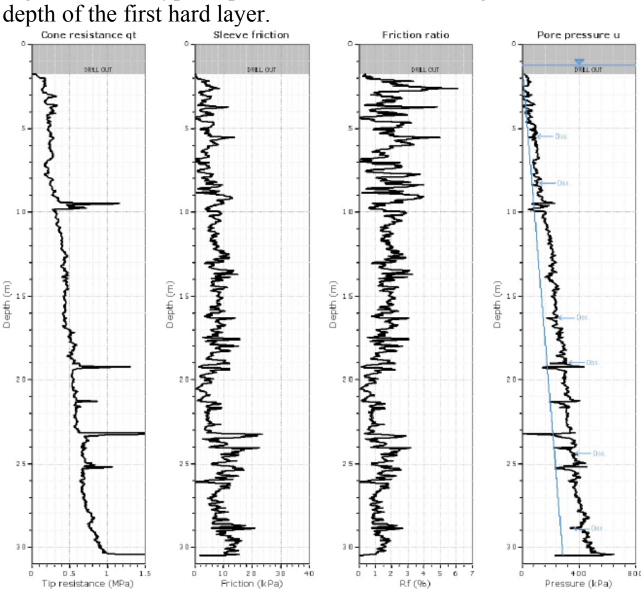

Figure 2. Probes with typical digital piezocone in the lacustrine zone.

1.2.2 *Seismic dilatometer (SDMI)*

The Marchetti dilatometer is an *in situ* load test that consists in laterally expanding a circular membrane that is adjacent to a flat metallic pallet that is driven into the terrain using static or dynamic penetration, depending on the soil conditions. The parameters obtained during execution provided information to determine not only the properties of deformability and compressibility of soils, but also the shear resistance. The DMT can be complemented with a seismic module used to record the velocity of the shear and compressional wave (SDMT).

Based on the three expansion measurements obtained with the dilatometer (measures *A*, *B* and *C*), the dilatometer parameters are determined, including: the material index I_D, the horizontal tension index K_D, and the dilatometer modulus E_D, and later, by correlations, diverse mechanical properties of the soil are determined (*e. g*., oedometric module *M*; non-drained shear resistance, s_u; the over-consolidation ratio, *OCR*; the lateral earth pressure coefficient at rest, K_0; angle of internal friction ϕ' and unitary weight γ). On the top of the dilatometer is a seismic module that allows the registration of the velocity of shear waves V_s as they hit the surface of the terrain (Fig. 3).

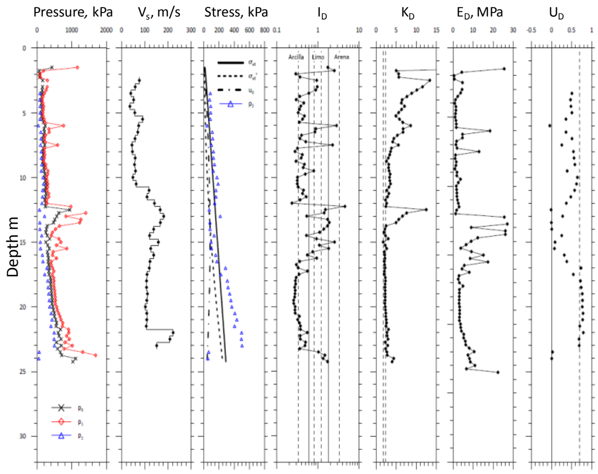

Figure 3. Results obtained with the seismic dilatometer

1.2.3 *Vane shear test (VST)*

An instrumented and automatized VST measures non-drained s_u, residual s_{ur}, and remolded $s_{u\_remolded}$ resistances of the soil *in situ*, where the torque applied is measured directly at the testing depth (ASTM D2573). The motor of the vane is programmable, so it is possible to modify the velocity of spinning for a specific angle and evaluate the non-drained peak and residual resistance, to later perform remolding at a higher velocity than the test velocity and finally lower the spinning velocity in order to now evaluate the remolded resistance.

1.2.4 *Geophysical methods*

SL method measures the shear velocities and compression waves in the ground by means of a low-frequency acoustic probe that "suspends" at different depths inside the bore, filled with water or drilling fluid. The probe is positioned at the depth required and the source fires, generating waves that propagate into the surrounding material in parallel to the drill shaft.

MASW is based on the measurement of surface seismic waves generated by a seismic source. In synthesis, the conventional procedure is made up of three phases: Data acquisition, analysis of dispersion (obtaining dispersion curves for each registry) and inversion (determination of the shear velocity profile of the subsoil, reflecting the theoretical dispersion that is closest to the dispersion curve obtained).

The SPAC method analyzes microtremor data from an array of stations (Aki, 1957): cross-correlation functions are computed between pairs of stations, and then averaged for different station pairs, at the same interstation distance but with different orientations. The objective is the calculation of the phase velocity for each frequency detected in seismograms in order to estimate the structural model of velocities.

1.2.5 *Laboratory test*

Close to the VST, SMDT and CPTu tests a selective borehole was performed using a soft soil sampler with double. The following laboratory tests were performed: natural humidity, consistence limits, unidimensional consolidation, Triaxials TX-CU and TX-UU.

1.3 *Correlations*

There are several empirical relationships that are used to determine mechanical properties using the results obtained with the CPTu and the SMDT. For the Mexico City clays, the correlations used have been based on tip resistance, q_c, and the intermediate parameters of the dilatometer K_D, I_D, and E_D, and are the following (Santoyo *et al*. 1989; Ivan & Mayne 2006; Ovando, 2013):

$$s_u = \frac{q_c}{N_k} \quad (1)$$

$$m_v = \alpha - \beta(\ln q_c) \quad (2)$$

$$k_o = 0.31\, k_D^{0.2} \quad (3)$$

$$OCR = 0.9\, k_D^{0.25} \quad (4)$$

$$c_u = 0.22\, \sigma_{vo}(0.5\, k_D)^{1.25} \; for \; I_D > 1.2 \quad (5)$$

where m_v, is the modulus of volume compressibility; N_k, is a cone factor that depends on the geometry of the cone, the rate of penetration and the OCR; σ_{vo}, is the total vertical stress; and α and β are correlation coefficients. Santoyo *et al*. (1989) showed that for Mexico City clay, the non-drained shear resistance is directly proportional to q_c, and the value of N_k depends on the degree of pre-consolidation, so the value of σ_{vo} that usually appears in the denominator of eq. 1, subtracting q_c, is not used.

2. RESULTS

Three sites were studied in the Valle de Mexico, all located in the Texcoco Lake site, in order to verify correlations 1 and 2, taking into account standard ISO 22476-1:2012, in which the penetration speed is 2cm/s and not 1cm/s, as used before. In addition, the value of q_T is considered instead of q_c

2.1 Correlations

The results of vane tests were compared to the measurements of CPTu and the value of N_{kT}, empirical cone factor for q_T, was obtained in experiments in all three sites studied. It is important to mention that the available literature does not clarify which type of stress is used in the numerator of eq 1 to obtain N_{kT}, in other words, the total stress (q_c-σ_{vo}), or the effective stress, σ'_{vo}, or if it is simply eliminated. As well, this paper study the empirical relationship between the non-drained remolded resistance with the sleeve friction, and the compressibility properties with the tip cone resistance.

2.1.1 Peak non-drained resistance

The measurements of resistance determined with the VST are compared, at one depth, with the values of N_{kT} expected using the tip resistance q_T. Below are shown three exercises in which the total and effective vertical stress are used and without considering the vertical stress, in order to obtain N_{kT} (Fig. 4). It can see that the relationship with the best correlation coefficient (ρ=0.88), is when the effective stress is taken into account in eq 1 (case b), in other words (q_T-σ'_{vo}), with a N_{kT}=10.7, which is a value very close to the minimum reported in the literature (Remai 2013). It is important to mention that in the case in which the vertical stress is ignored (case c), a similar correlation coefficient is obtained (ρ=0.86), with a N_{kT}=12.7, which is close to the one considered when using the q_c.

2.1.2 Remolded non-drained resistance

In cases of remolded resistance measured in the field with VST, the measurements were compared to the sleeve friction of the CPTu (Fig. 5). In this case, we can see a direct relationship between these two parameters. While the sleeve friction is the least trustworthy of the parameters measured, the correlation shows that a good approximation to the undrained remolded resistance is obtained (eq 6).

$$s_{u(remolded)} = f_s \quad (6)$$

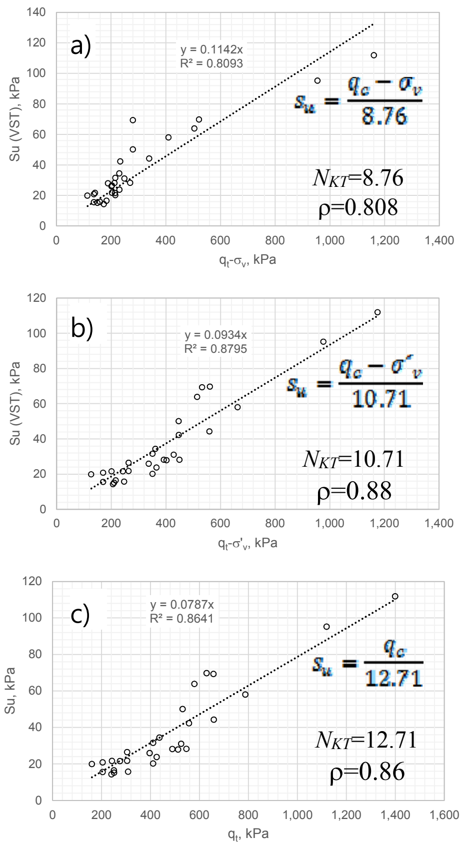

Figure 4. Estimation of the peak non-drained resistance considering: a) the total vertical stress, b) the effective vertical stress, and c) no stress.

2.1.3 *Compressibility*

Compression and recompression indexes, C_c and C_r, were compared with respect to the corrected tip resistance q_T (Fig 6). As it can see, there is a correlation when compared to C_c and not when compared to C_r. The correlation obtained in order to determine C_c as a function of q_T (eq. 7)

$$C_c = 217.63\,(q_T)^{-0.599} \quad (7)$$

2.2 *Profiles of short wave shear*

The profiles of the velocities of shear wave were determined in the three sites studied using SL, MASW, SPAC and SDTM techniques (Fig. 7). In Fig. 7a shows that SL, which produce some ground alteration, and the seismic dilatometer, practically show the same results. As well, using the MASW method, similar results are obtained, although with less detail with respect to those obtained using the DMTs and LS techniques. In Fig. 7a&b show velocity profiles for sites 2 and 3, determined using SL, SDMT and SPAC. We can see a good approximation, with greater detail in the profile obtained using SMDT.

2.2.1 Determination of velocity profile on terrain with alternating soft and hard layers

Frequently the soil deposit is composed of alternating hard layers with soft soil deposits, which makes SDMT testing more difficult, due to the fact that this tool does not go through the hard layers when they are of a certain thickness. In order to overcome this obstacle, it is feasible to drill a borehole, and later fill in with fine gravel, later only the seismic modulus of the dilatometer is driven in a conventional way to obtain the variation in the velocity of the shear wave, even in hard layers. In Fig. 8 shows the results of a test done with a conventional SMDT, using a borehole filled with sandy gravel. As we can see, the results are practically the same.

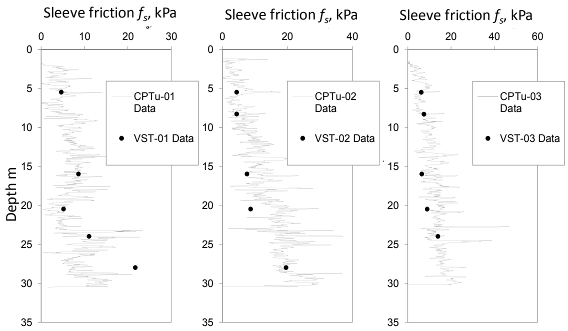

Figure 5. Comparison between the sleeve friction of the CPTu, f_s, and the remolded resistance measured using VST, $s_{u\_remolded}$.

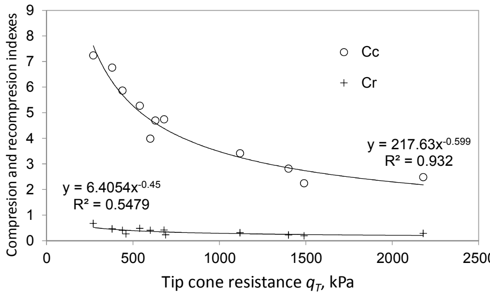

Figure 6. Correlation between corrected tip cone resistance and compression and recompression indexes.

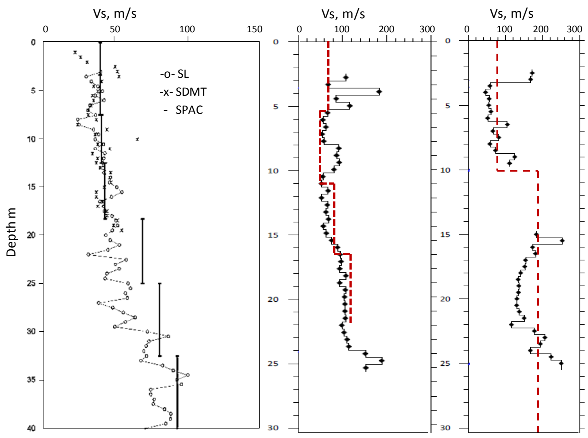

Figure 7. Shear velocity profiles for site 1 (a), 2 (b) and 3 (c) (SDMT-solid line and SPAC-dashed line, figs 5b &5c).

3. CONCLUSIONS

From the results found as derived from the association of the different techniques observed, we reach the following conclusions with respect to the CPTu testing:

It is necessary to take into account the correction of tip resistance for the pore pressure generated during cone driven. If not, the non-drained resistance value will be underestimated.

The best empirical relationship between the q_T *vs.* s_u, was obtained using the effective vertical stress, where N_{kT}=10.7. Similar results are obtained with no vertical stress parameter.

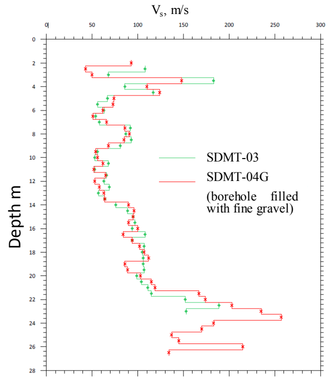

Figure 8. Profile of shear wave velocities determined using SMDT driven in natural ground or in a borehole filled with fine gravel.

For Mexico City soils, the sleeve friction in the CPTu is a good estimation of the remolded resistance, based on the comparison of the results of the VST, and there is a high correlation between the compressibility index C_c and the resistance q_T, however, the correlation with the C_r is low.

Based on results obtained in the determination of shear wave velocity profiles in clay deposits using different field techniques, we have reached the following conclusions:

Whereas each of the methods generates a different level of deformation and ground alteration during testing, the results obtained in the lake deposits in Mexico City indicate that any technique will produce similar results. Considering the different characteristics of each of the exploration techniques indicated in this paper, the choice of a test to be used will depend on the depth of exploration and the detail required in the exploration campaign. In general, a suspension logging and a seismic dilatometer detail the velocity profile but the MASW and SPAC techniques can reach greater exploration depths. In the best practice, all of the methods complement each other.

In order to increase the depth and give continuity to the shear wave velocity profile obtained using a seismic dilatometer in terrain where there are hard layers, it is possible to drill a borehole and fill it with fine gravel in order to drive the dilatometer. The results obtained are practically the same as when performing the driving in natural ground. Using the seismic dilatometer technique, it can be obtained a better image of the ground because it is possible to directly or indirectly determine additional mechanical parameters in the subsoil.

4. REFERENCES

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