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Validation of some CPT correlations for highly compressible soft clays

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ABSTRACT: This paper presents the validation of some cone penetration test correlations for highly compressible soft clays, such as the Mexico City Clay, including soil characterization, strength and seismic parameters based in their comparison with laboratory and field tests results performed at the east and south east of Valley of Mexico, which is a region known for the presence of important thicknesses of clays and silts deposited in a lacustrine environment, with very particular properties, such as a high compressibility, as well as water contents above 300% and very low shear stress resistance. The tree parameters obtained from the field tests: the tip resistance (qt), the friction force in the cone sleeve (fs) and the dynamic pore pressure (u) during the pushing of the tool, which analysis was found to fit with the very well-known stratigraphy of the Valley of Mexico, allowing to adjust locally the depths of the characteristic layers of the zone and indicators associated with geological processes such as volcanic emanations and desiccation events.

Keywords: CPTu; SBT; Seismic properties; CPTu Correlations; Sensitive clays

1. General description and antecedents of the tested soils

The sensitive clays of the Valley of Mexico were deposited in a lacustrine-volcanic environment interbedded with volcanic ashes and lake dissections. Those soil layers kept naïve till the Spanish Colony, when the lakes started to be permanently dissected in order to build the Mexico City and surroundings. Nowadays, almost all of the former waterbodies are out of water or confined into pipes. Instead of them, buildings houses and industries were raised.

The most undisturbed zone is located in the southeast side of the valley due to its slow metropolitan development and also related to the former lake conditions at that area.

The former lake typical stratigraphy [1, 2] basically consists of two silty-clayey layers divided by a silty-sandy layer; and their geotechnical properties are well known, being used to get water contents ($w\%$) above 300%, unit weights (γ) next to the water one (1.15 to 1.25 t/m^3), a undrained shear strength resistance between 0.5 to 1.0 t/m^2 in the upper clays and between 3 to 4 t/m2 in the lower strata; and the compressibility (m_v) between 0.01 and 0.3 cm^2/kg.

Dynamically, soils of that zone usually present a shear wave velocity, V_s, between 40 and 140 m/s. for clay deposits.

1.1. Available CPTu tests in the zone

A universe of 750 m of CPTu tested soil was considered for this paper, having depths up to 80 m. Their locations are shown in Fig. 1. Sites such as Ecatepec, Circuito Mexiquense, Reforma and Colonia Roma were studied merely about seismic properties correlations, while the 500 m which correspond to sites of Ignacio Zaragoza,

Rojo Gómez and Tlahuac were also used to verify the soil behavior and unit weight correlations.
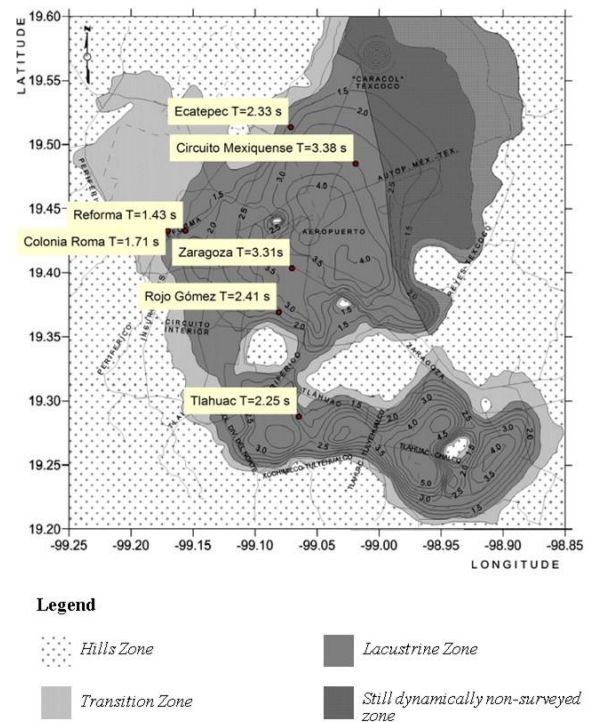

Figure 1. Location of the considered CPTu tests, into de Valley of Mexico.

2. Validation of SBTn and I_c correlations

2.1. Soil Behavior Type (Robertson) characterization

Robertson (2010) [3, 4] stated updates for his empirical CPTu characterization criteria based on the Soil Behavior Type (SBT) which is determined according to the three cone parameters (Q_t, F_s and u),

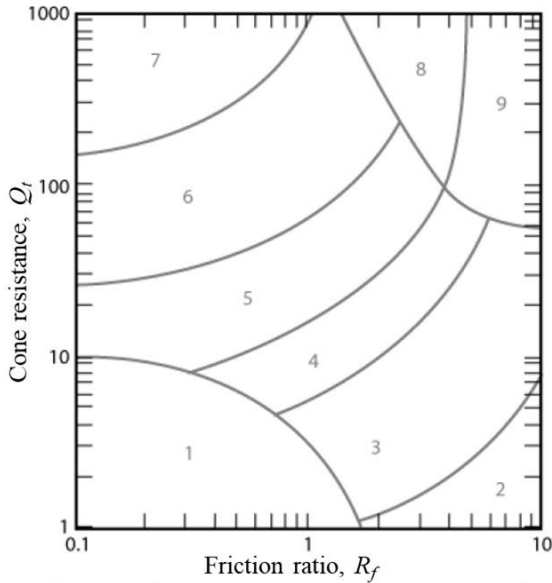diferentating the behaviour in nine kinds, from sensitive fine grained soils to very stiff fine grained soils.

The difference between those criteria is that the first one (Fig. 2) is based on the simple parameters q_t (= q_c/p_a) and R_f (=f_s/q_t), while the normalized criterion (Fig. 3) uses the normalization of the same parameters about the overburden stress (Q_{tn} and F_r, respectively). The parameters can be calculated as follows (Eq. 1 and Eq. 2):

$$Q_{tn} = (q_t - \sigma_{vo})/\sigma'_{vo} \qquad (1)$$

Where σ_{vo} is the in situ vertical stress and σ'_{vo} is the in situ effective vertical stress.

$$F_r = f_s/(q_t - \sigma_{vo}) \qquad (2)$$

Where f_s is the friction sieve and F_r, can be expresed also as a percentage (mulpiplying the ratio by 100).

Figure 2. Soil behavior type characterization (Roberson, 1986 updated by Robertson, 2010) [3].

The normalized criterion uses a Index of type, I_c, in order to have a more objetive determination of the SBT. This index is evaluated as fillows [2] (Eq.3):

$$I_c = \sqrt{(3.47 - \log Q_t)^2 + (\log F_r + 1.22)^2} \qquad (3)$$

Additionally, Roberton also proposed an update [3] about the CPT characterization, considering claylike and sandlike, as well as dilative and contractive behaviours (Fig. 4). In this case, the SBT is cuantitatively defined according to the Modified Soil Behaviour Type Index, I_B, whixh can be calculated as follows [4] (Eq. 4):

$$I_B = 1000(Q_{tn} + 10)/(Q_{tn}F_r + 70) \qquad (4)$$

In this case, I_B= 22 is the lower boundary for the sandlike ideal soils and is relative with Ic for SBTn 4 and

5 zones. At the same time, I_B= 32 indicates the boundary for most of the clay-like ideal soils, which is correlacionable with the SBTn for zones 3 and 4 for normally consolidated soils. And the transitional zone between claylike and sandlike ideal soils is located when I_B goes from 22 to 32.

In addition, the boundary between contractive and dilative soils is placed when CD is around 70, being that it can be calculated as indicated by Eq. 5.

$$CD = (Q_{tn} - 11)/(70 + Q_{tn}F_r) \qquad (5)$$

Some other considerations about it must be considered in case of predominantly dilative soils at large strains.
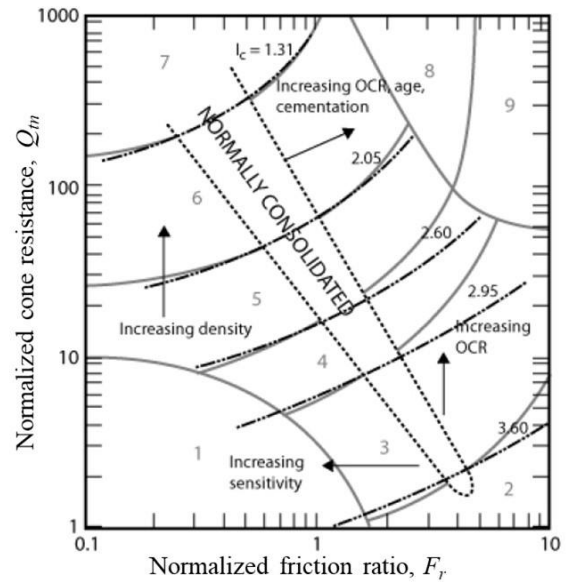
| Zone	Normalized Soil Behaviour Type (SBTn)	I_c
1	Sensitive, fine graded	N/A
2	Organic soils – clay	>3.6
3	Clay – silty clay to clay	2.95 – 3.60
4	Silt mixtures – clayey silt to silty clay	2.60 – 2.95
5	Sand mixtures – silty sand to sandy silt	2.05 – 2.60
6	Sands – clean sand to silty sand	1.31 – 2.05
7	Gravelly sand to dense sand	< 1.31
8	Very stiff sand to clayey sand*	N/A
9	Very stiff fine grained*	N/A

* Heavily overconsolidated or cemented

Figure 3. Normalized Soil behavior type characterization (Roberson, 1990 updated by Robertson, 2010) [3].

2.1.1. Validation process

As mentioned above, around 500 m of CPTu of Mexico City subsoils were tested to verify their match with the SBTn characterization [3, 4].

The initial step was to observe the *accuracy* of the SBTn criterion according to the particular but well-known Mexico City stratigraphy. For that, all of the CPTu tests were processed according to get the I_c and SBTn expressions. For instance, figures 5 and 6 show the obtained results from a couple of the processed boreholes.
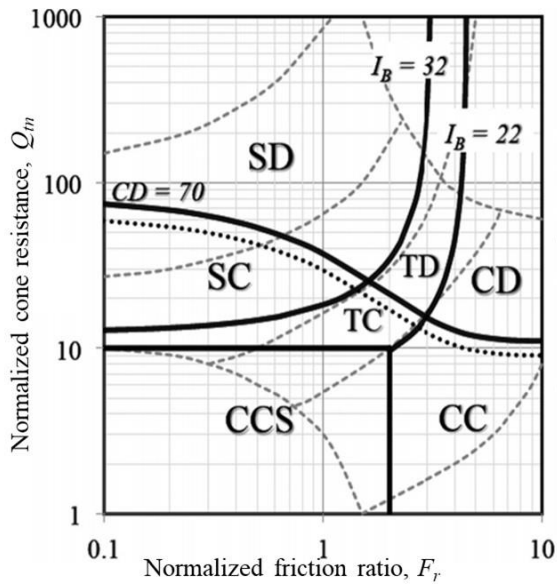
Zone	Soil Behaviour Type (2016)
1	CCS, Clay-like – Contractive – Sensitive
2	CC, Clay-like – Contractive
3	CD, Clay-like – Dilative
4	TC, Transitional – Contractive
5	TD, Transitional – Dilative
6	SC, Sand-like – Contractive
7	SD, Sand-like – Dilative

Figure 4. Normalized Soil Behavior Type update [3] (solid lines show soil behavior type boundaries according to I_B, and dashed lines show the originally suggested boundaries)
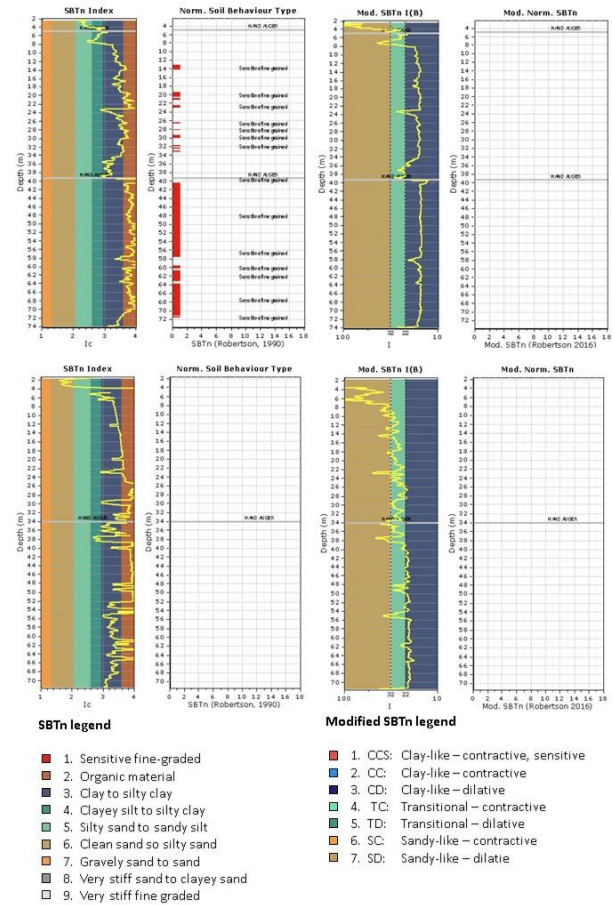

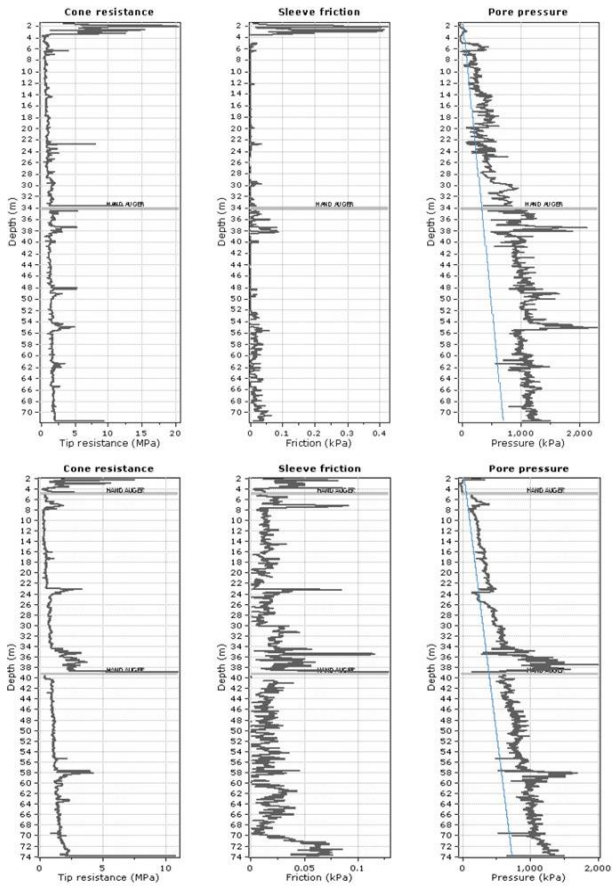**Figure 6.** Examples of tests performed eastwards of the Valley of Mexico.

The results of that exercise are plotted in Figs. 7 and 8, related with their corresponding typical strata: CS is the superficial strata conformed by sun exposure dissected clays and anthropic landfills. Typically, this stratum is heterogeneous and its properties can vary significantly; SAS refers to the shallow lacustrine clays deposits that may be intercalated with silts; CD refers to the silty-sandy buried desiccated strata which divide the SAS from the deep lacustrine clays stratum, referred as SAI.
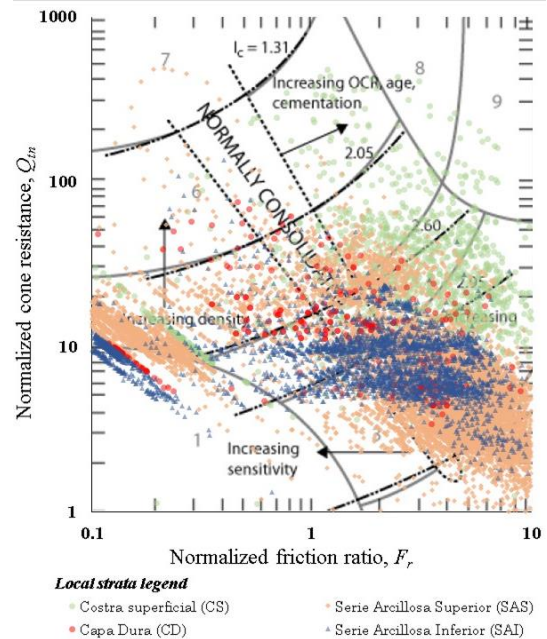

Figure 5. Examples of tests done eastwards of the Valley of Mexico.

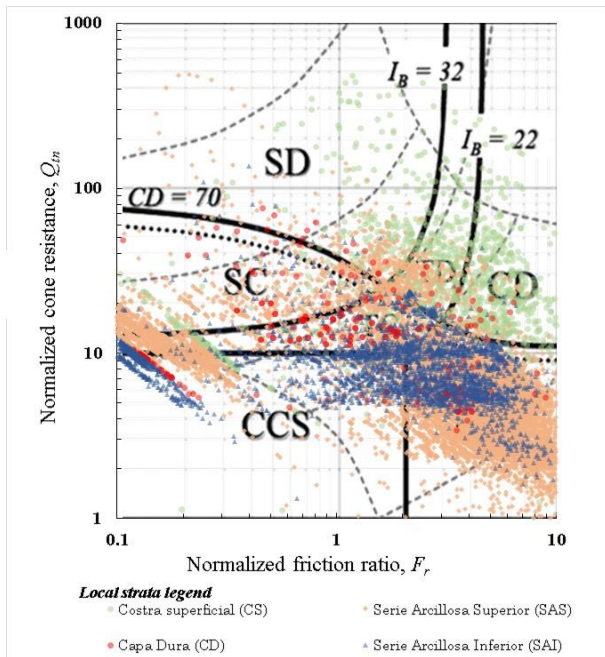**Figure 7.** Results of the SBTn site characterization [2].

Figure 8. Results of the SBTn site characterization plotted over the SBTn update [3].

2.1.2. Unit weight correlation

Roberton [3] also states many correlations to determine properties such as unit weight, OCR and undrained shear stress resistance. A comparison between those correlations and laboratory tests results were also performed and are presented herein.

Acording to the mentioned reference, the relationship between the in situ unit weight (γ) and the water unit weight (γ_w) can be determined based on Eq. 6, which is showed bellow. Hence, γ can be determined just by multimplying those reuslts by γ_w.

$$\gamma/\gamma_w = 0.27[logR_f] + 0.36[log(q_t/p_a)] + 1.236 \quad (6)$$

A comparison between the estimated unitweights and the actual unit weights, obtained in laboratory at the same location are plotted in Fig. 9.
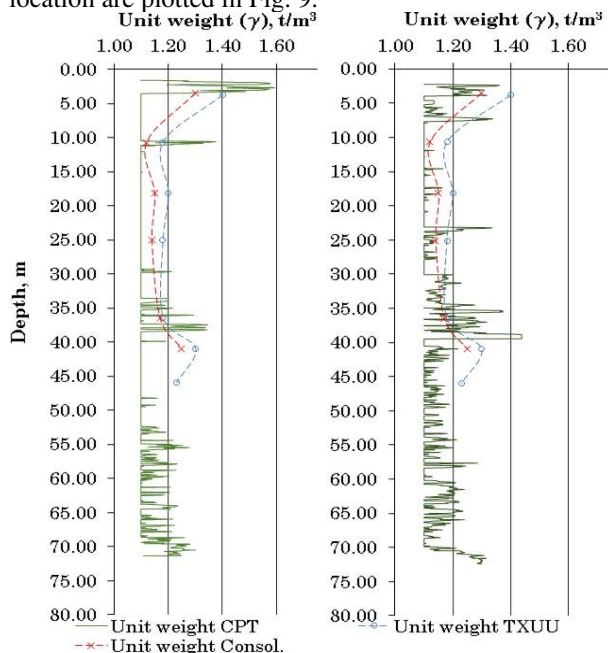

Figure 9. Comparison between CPTu-estimated weights and laboratory-obtained unit weight.

3. Estimation of dynamic properties from CPT tests

When information from field tests for dynamic properties is not available or there is no possibility to run these kind of tests, it is possible to resort to empirical correlations based on CPT data to estimate dynamic properties.

3.1 Estimation of V_s

Ovando and Romo [5] presented mathematical expressions that correlate the CPT tip resistance for the clays of Mexico City, such as its sandy lenses, derived from cavity expansion theory and hyperbolic models. Since its publication, this correlation has been widely used for soils in Mexico Valley. Mathematically, it is as shown in Eq. 7:

$$V_s = \eta \sqrt{\frac{q_t}{N_{kh}\gamma_s}} \quad (7)$$

Where γ_s is the unit weight of the soil, qt is the tip resistance for CPT in t/m2 an N_{kh} and η are dimmensionles factors proposed by Ovando and Romo [5] for the soils of the Mexico Valley, as shown in the table 1:

Table 1. Factors N_{kh} and η by Ovando y Romo

Soil type	N_{kh}			η
	Min.	Med.	Max	
Preconsolidated Texcoco Lake clays	14.0	9.5	6.7	23.33
Xochimilco and Chalco clays	14.0	9.9	7.0	26.40
Sands and silts from hard lenses	16.0	11.1	8.0	40.00

This correlation has been used in tests for Xochimilco-Chalco and Texcoco clays in this research, startin with Fig. 10, which is a tip resistance graphic for a CPT test ran in "Circuito Mexiquense" highway (see Fig. 1 la del mapa), at the northeast of the Mexico Valley, corresponding to Texcoco Lake clays.

Eq. 7 was applied to CPT data form Fig. 10 (a), in order to obtain resulting Vs for this location, which is shown in Fig. 10(b). The unit weigth of the soil was calculated using Eq. 6.

Same procedure was repeated for Tlahuac (see Fig. 1), which data is presented in Fig. 11(a), giving the results presented in Fig. 11(b) that correspond to Xochimilco and Chalco Lake clays.

These results were compared with information from the historical archive of "Sísmica de Suelos" (2010-2018), an organization with a wide experience in field test for dynamic properties in Mexico Valley. From there, were observed tipicall values for characteristical layers for Mexico Valley deposits showing that for most superficial deposits, afected by processes like solar dry, V_s can reach 120 m/s, while for clay it ranges from 50-90 m/s. Sandy hard layers embedded in clays show values up to 120 m/seg. Values observed in Fig. 11 and 13 are slightly higher for surface materials and sandy lenses and hard layers, and tend to fit very well for clays.
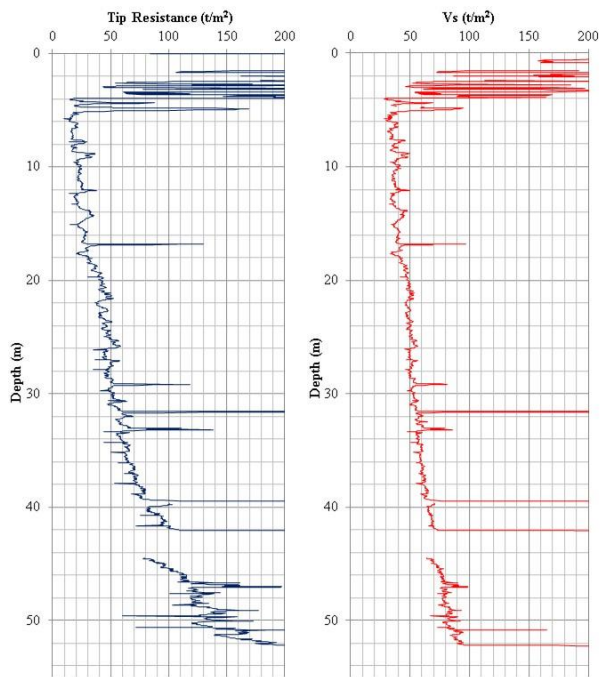
a) q_c obtained at Circuito Exterior Mexiquense.
b) V_s estimation based on Ovando and Romo (1990) for the same site.
Figure 10. Tip Resistance for Circuito Mexiquense.
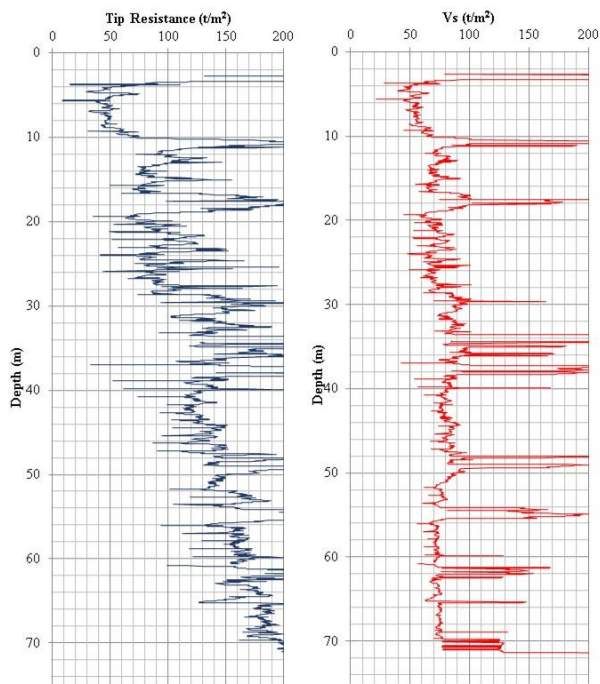
a) q_c obtained at Tlahuac.
b) V_s estimation based on Ovando and Romo (1990) for the same site.
Figure 11. Tip Resistance for Tlahuac.

Also, Solano [9] presented a resume for typicall geotechnicall values for Mexico Valley, as shown in table 2. It is important to mention that ranges presented in table 2 are wide because this research had a regional character.

Table 2. Factors N_{kh} and η by Ovando y Romo.

Layer	q_t (t/m^2)	V_s (m/s)
Superficial deposits	>200	120 – 280
Clay deposits	<200	40 – 120
Sandy hard layers	>200	80 – 350

Again, results for V_s shown in Fig. 11 and 13 tend to fit well with previous data.

3.2 Estimation of T

Vibration period of the soil mass was estimated using average values of V_s for a borehole of length H, in order to apply Eq. 8. This expression has previously been used frequently by numerous researchers [6].

$$T = \frac{4H}{V_s} \tag{8}$$

Eq. 8 was apllied in this research for al locations showed in Fig. 1 (Circuito Mexiquense, Colonia Roma, Reforma, Ecatepec, Colonia del Mar, Tlahuac and Rojo Gomez). Periods calculated with Eq. 8 tend to fit very well to the isoperiod map in Tlahuac, Tlahuac and Reforma, but also shows important variations y the rest of locations. Both Eq. 8 and isoperiod map from Fig. 1 are preliminary tools for estimating T, so results obtained by these metods can be usefull in first stages of a research, but never in specific tasks like construction of seismic design spectre [7-10].

4. Conclusions

The SBTn results for CPTu tests performed eastwards from the Valley of Mexico trend to match with the well-known stratigrafy of that region [1, 2]. Morever, the application of these criteria (nonmodified and modified) allow to find behavior differences, some particularities and singularities at each strata, mainly if some I_c correlations are applied [3, 4].

It is particularly helpful to find changes in soil behavior and to find out potential ones in soil properties, which is crussial to recognize in many of the issues commonly analyzed by geotechnical practitioners.

Regarding on the I_c correlations [3, 4], such as the unit weight one, it would be usefull to look for additional correlation(s) to be applied in cases when the SBT index can not be estimated due to their extremely low q_c. For instance, sensitive fine-graded soils, like many of the surveyed at former naïve Texcoco and Chalco Lakes.

Estimating values for Vs using the empirical correlation proposed by Ovando and Romo [5] can lead to results that fit very well to those obtained through field tests. Although, they propose to assume the values of unit weights according to the nature of the materials, calculating them using Eq. 6 from Robertson and Cabal [3, 4] increases the accuracy of the results.

Estimating values for T from empirical correlation like those [5] showed in this research have considerable deviation with values obtained through field tests [10]. So, this kind of results should only be used like initial references.

Acknowledgement

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