Calibration of the CPTu and analysis for lacustrine deposit of Bogotá

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ABSTRACT: It is possible to calculate multiple parameters useful for soil characterization and geotechnical design through the use of the CPTu. Most of the geotechnical parameters that can be obtained from the CPTu are defined by empirical correlations that require calibration and verification with other subsoil exploration techniques and laboratory tests. This article presents a geotechnical characterization of the Bogotá lacustrine deposit and the results of the calibration of the undrained shear strength Su. This parameter depends on the net tip resistance measured with the CPTu, the effective vertical stress and the Nkt factor, which has a high degree of uncertainty in fine grained soils such as those that make up the Bogotá lacustrine deposit. A soil exploration campaign that included 140 boreholes and 90 CPTu that reached depths of up to 50 m distributed throughout the study area was provided for the calibration.

Keywords: CPTu; Undrained shear strength Su; Nkt; lacustrine deposit; soft clays.

1. Introduction

1.1. Study zone

The metropolitan area of Bogotá is located in the center of Colombia, in the eastern mountain range at approximately 2600 meters above sea level (masl) at a latitude 4 ° north and longitude -74 ° west. It is part of the former sedimentary lacustrine basin of the Bogotá Savanna, which has been affected by events of accumulation of sediments of great thickness and compressive processes that, caused folding and failure in the northeast direction, as a result there is a mountainous and undulating topography in the most prominent part of the savanna, and plain-like landscapes associated with quaternary lake deposits.

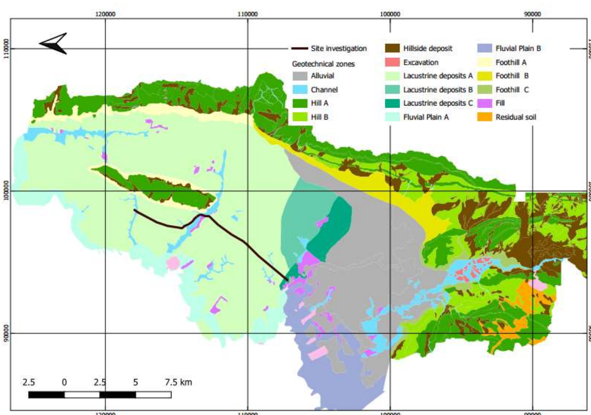

Fig 1. Geotechnical zoning map of Bogotá

Fig 1 shows the distribution of the geological units of Bogotá. The Eastern Hills that frame the geography of the city on the eastern side, are made up of firmer soil. In the western zone, rocks from the quaternary period prevail, formed in river-lagoon environments thah include flood plain and high terrace. These geoforms are associated with erosion and sedimentation processes historically caused by the Bogotá river, its tributaries and other glacial processes.

The deposit located in the Bogotá basin has a thickness of 586 m, according to the research done by Torres et al [1]. Sedimentation and deposition of the first 325 m of soil was lake-like and temporarily interrupted. Currently, the deposit has an overconsolidated surface layer above soft clay soils that prevail in depth. Diatomaceous particles are present in the soft clay and modify the mechanical behavior of the soil [2].

Over 60% of the urban area of the city is founded on this lacustrine deposit, characterized by its very soft consistency, which implies low bearing capacity and high consolidation settlements. The conditions in this area generate an important challenge in the design and construction stages of infrastructure projects.

1.2. Field and laboratory tests

As part of the linear infrastructure projects that are being developed in the city, 140 boreholes with variable depths between 6 m and 100 m were carried out in the Bogotá lacustrine deposit, from which more than 1000 unaltered samples were extracted with thin walled shelby tubes, in which classification, compressibility and resistance tests were carried out.

In addition, 90 Cono Penetration Tests with pore pressure (CPTu) were carried out distributed throughout the lacustrine deposit with varying depths between 12 m and 50 m, as shown in Fig 2.

Six sites with higher exploration density were select in the study zone, wich had the deepest exploration and more field and laboratory tests. Fig 3 and Fig 4 show the location of the boreholes and piezocone tests of sites 2 and 3.

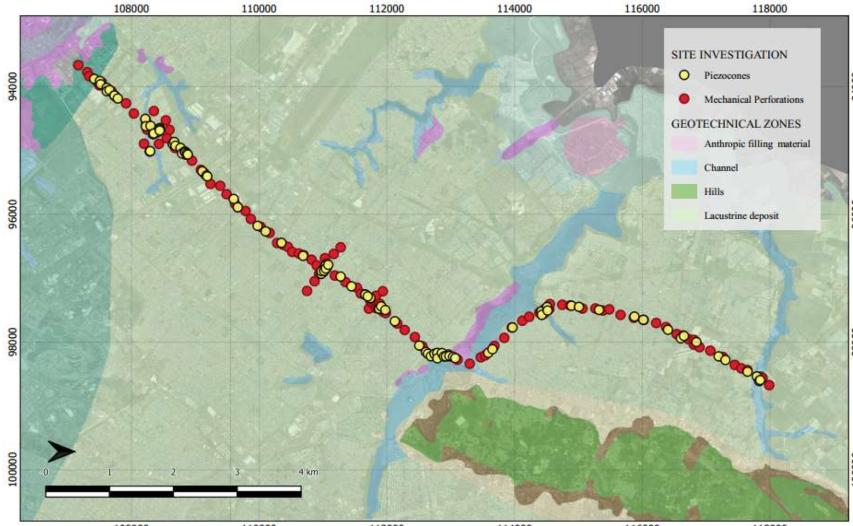

Fig 2. Geotechnical site investigation location plan

Fig 3. Site Investigation location plan - Site 2

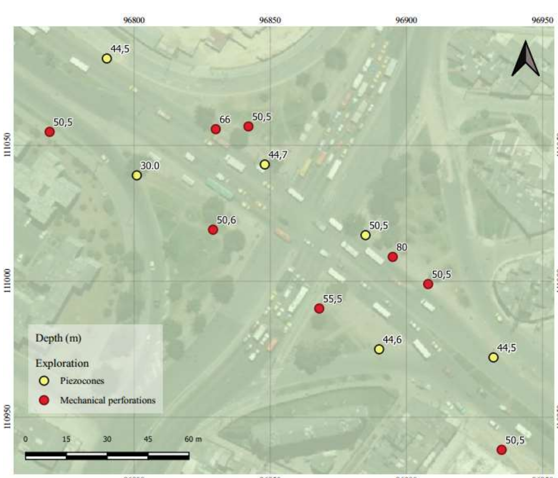

Fig 4. Site Investigation location plan - Site 3

2. Geotechnical characterization of the Bogotá Lacustrine Deposit

Classification and index properties tests were complet, comprising water content, Atterberg limits and particle size distribution tests.

According to descriptions from the borehole reports information obtained from the mechanical perforations,

there is an anthropic fill overlying the deposit, up to 5 m thick in some areas of the deposit, with an average thickness of 2 m. Furthermore, two sandy strata were found in the soil profile:

1. Depths of between 65 m and 76 m below ground level sand content are up to 87% with an average value of 26%, and
2. Depths of between 88 m and 100 m below ground level with a 46% sand content. The remaider of the deposition is mainly fine grained particles.

Of the state parameters obtained in the boreholes, a high range in water content (Wn) is observed in the upper profile with a coefficient of variation of 20%. The graph in Fig 5 shows an increase to an average value 156% in the overconsolidated stratum. At depth the water content decreases until it stabilizes at an average value of 50%, as shown in

. While the plastic limit (PL) remains constant with depth, with an average value of approximately 40%, the liquid limit (LL) exhibits a behavior similar to that of water content, with a maximum value above 380%. The void ratio (e_o) increases from 1 to 4 in the first 20 m and decreases to an average value of 1 at the maximum exploration depth.

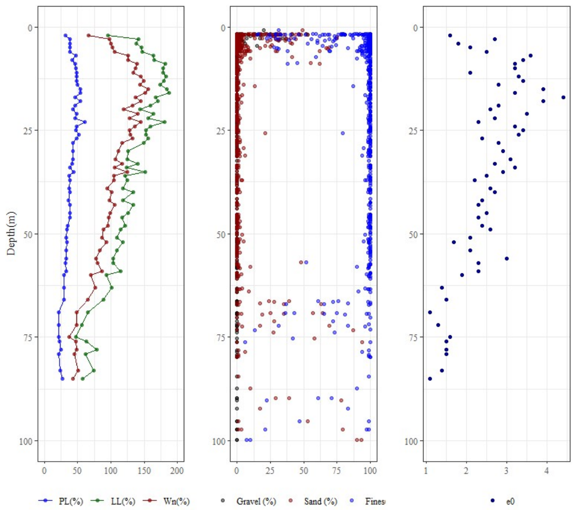

Fig 5. Average index properties

3. CPTu Calibration

Based on the measured cone tip resistance q_c, sleeve friction resistance f_s and pore water pressure behind the cone u_2 recorded during the CPTu, parameters of geotechnical interest can be calculated, that allow the definition of the state of stress, resistance and compressibility.

3.1. Soil behavior type index

One of the greatest advantages of the CPTu test is the characterization of the soil type simultaneously with the penetration of the cone by correlating the parameters measured in the tests and the mechanical response of the soil located in the vicinity of the tip.

The Soil behavior type index (Ic) depends on the normalized cone tip resistance Q_t and the friction ratio F_r, and defines nine behavior zones. The Ic valuesvary between values greater than 3.6 for fine-grained sensitive soils and less than 1.31 for dense or gravelly sand [3].

The Soil behavior type index, Ic, for the lacustrine deposits was calculated using the Eq. (1).

$$I_c = [(3.47 - logQ_t)^2 + (log\, F_r + 1.22)^2]^{1/2} \quad (1)$$

The results obtained for each of the 90 CPTu carried out in the study area were compared with the material description from the boreholes and laboratory test results, finding an equivalent soil classification.

The Ic values obtained in all CPTu vary from 2.2 to 3.5 in the first 10 m and remain constant up to 50 m depth, with an average value of 3.4, wich correlates to a clay to silty clay classification.

3.2. Unit weight

620 unit weight values were obtained from laboratory testing on undisturbed samples extracted from boreholes. The unit weigth parameter is required for the calculation of the effective stress, wich is used to calculate the undrained shear strenght Su. The lab data was compared to the CPTu results.

Throughout the deposit, the values obtained in the laboratory have a considerably high range, between 11 kN/m^3 to 19 kN/m^3.The maximum value was obtained in the near surface layer. The variation in values is lower at greater depth.

Between 5 m and approximately 20 m, the unit weight results suggest the existence of an overconsolidated stratum, due to the formation of the deposit and variations in the water table [1], with values between 12,7 kN7m^3 y 14 kN/m^3. Between 20 m and 50 m, presenting a variation of 13 kN/m^3 to 14 kN/m^3. At greater depths the unit weight vary between 14 kN/m^3 and 17 kN/m^3.

Based on the results of the CPTu, the unit weight of the soil is commonly calculated in Colombia as a function of the frictionratio (R_f),the tip resistance (q_t), unit weight of water (γ_w) and atmospheric pressure (Pa), according to Eq. (2) [4]:

$$\gamma_t = \left[0.27\, log(R_f) + 0.36\, log\left(\frac{q_t}{Pa}\right) + 1.236\right]\gamma_w \quad (2)$$

Mayne [5] developed an expression for the evaluation of the unit weight based on the sleeve friction resistance (fs), unit weight of water (γ_w) and and atmospheric pressure (σ_{atm}), according to Eq. (3):

$$\gamma_t = [1.22 + 0.15\, ln(100 * f_s/\sigma_{atm} + 0.01)]\,\gamma_w \quad (3)$$

The unit weight values obtained from the two equations above are greater than the results obtained from laboratory tests.

The relationship between the unit weight and data from CPTu was evaluated throughout the deposit. The normally consolidated soil has a better correlation with tip resistance, while overconsolidated soil has a better correlation with sleeve friction resistance. Based on this behavior, the calibration of the model was performed with the results of all exploration, considering that dispersion measures have to be kept constant for all the deposit.

From a statistical analysis of this information, the dimensionless factors of Eq. (2) and Eq. (3) were adjusted, thus Eq. (4) and Eq. (5) were obtained.

$$\gamma_t = \left[0.38\, Log_{10}(R_f) + 0.015\, Log_{10}\left(\frac{f_s}{Pa}\right) + 1.2\right]\gamma_w \quad (4)$$

$$\gamma_t = \left[0.35\, Log_{10}(R_f) + 0.16\, Log_{10}\left(\frac{q_t}{Pa}\right) + 0.94\right] \gamma_w \quad (5)$$

In Fig 6, data measured in the laboratory and data calculated with Eq. (4) and Eq. (5) are compared in three differents sites. A low coeficient of correlation is obtained, however, the range of variation between the input and simulated values remains in the same range with a standard deviation of less than 1, therefore, the correlation is acceptable.

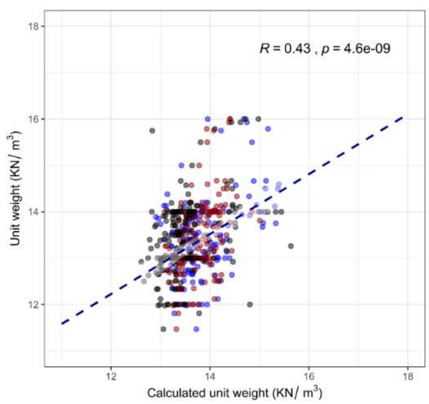

Fig 6. Soil unit weight obtained from qt and fs

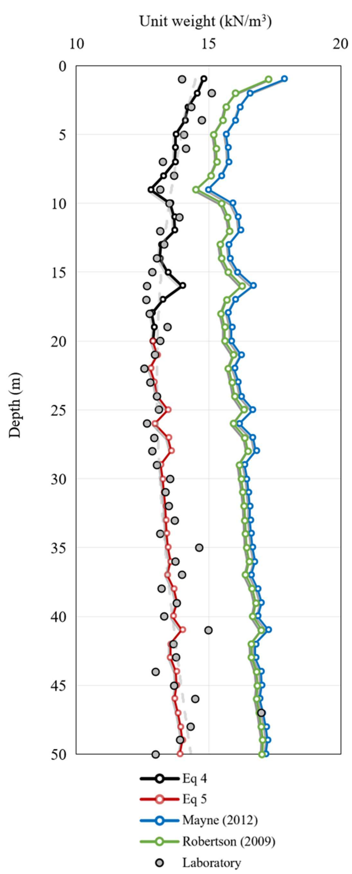

Fig 7. Unit weight measured in laboratory tests and calculated using correlations.

The correlation for unit weight based on a CPTu result located in Site 2 is presented in Fig 7 and ploted against the unit weight values obtained in the laboratory. The original correlations by Mayne [5] and Robertson [] are included for reference

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The correlations by Robertson and Mayne overestimated the unit weigth, by up to 3 kN/m^3. Despite the low correlation coefficient shown in Fig 6, the depth adjustment for each of the CPTu was verified with good correlation with respect to the site specific correlations.

3.3. Undrained shear strength

In general terms, the undrained shear strength can be calculated with the CPTu as the ratio between the net resistance at the tip of the cone q_{net} and the N_{kt} parameter. q_{net} is calculated as the difference between the corrected cone tip resistance q_t and the total stress σ_v, as in the following equation:

$$S_u = \frac{q_t - \sigma_v}{N_{kt}} = \frac{q_{net}}{N_{kt}} \quad (6)$$

The factor N_{kt} may have reference values between 6 and 20. However, this wide range can contribute to a misinterpretation of the undrained shear strength obtained from the CPTu, so a specific site calibration is necessary [6].

Shear tests were executed in the 140 boreholes in the study area, at maximum depths of 30 m, and then corrected for plasticity to allow Nkt values to be estimated.

A variation analysis was carried out on the magnitude of the undrained shear strength obtained from the shear tests, in order to facilitate the calibration. 12 zones were found in the 20 km that comprise the deposit, with homegeneous results. The net tip resistance of each of the cones was related to the Su obtained from the shear tests, through their average values at equivalent depths.

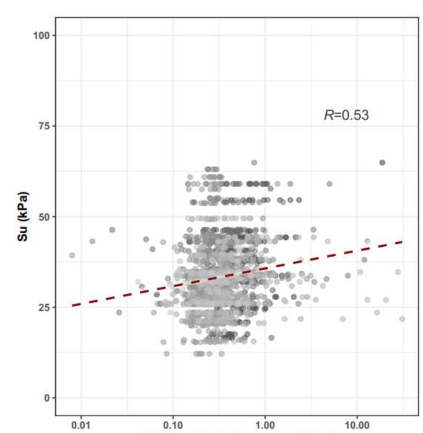

Fig 8. Su and net tip resistance

Using the previously described method, Nkt values were obtained at different depths for each of the piezocones throughout the deposit. Four zones were found in which Nkt values are applicable. Fig 8 and Table 1 present a summary of the shear tests and CPTu data compared for the calculation of the Nkt factor. The coefficient of variation is also presented for the results obtained in the deposit.

Table 1 Nkt results

ZONE	From (m)	To (m)	Nkt		
			Mean	**Standard deviation**	**Coefficient of variation**
1	1	7	15,5	3,8	24%
	7	18	12,5	2,3	18%
	18	22	15,8	4,3	27%
2	1	6	12,9	4,5	35%
	6	18	10,0	1,7	17%
	18	22	8,1	2,3	29%
3	1	4	15,9	3,4	21%
	4	11	16,0	3,9	24%
	11	22	15,3	1,5	10%
4	1	4	10,3	5,0	48%
	4	9	7,4	0,7	10%
	9	18	8,6	1,8	21%

In general, the Bogotá lacustrine deposit has an approximate length of 20 km. The coverage of the explored area corresponds to approximately 50% of the deposit. In the south-north direction, the determined zones from 1 to 4 have 1 Km, 4.5 Km, 1.5 Km and 3Km, respectively.

Fig 9 shows the undrained shear strength obtained for a CPTu selected in Zone 2, with a Nkt factor equal to the mean values in Table 1. The figure presents the undrained shear strength obtained in the shear tests and the undrained shear strength, calculated as 0.22 of the effective vertical stress, applicable for normally consolidated clays.

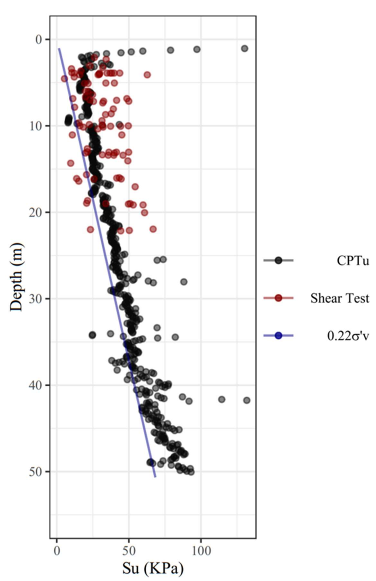

Fig 9. Su obtained for Zone 2 CPTu

4. Conclusions

Based on the results of the exploratory campaign carried out in the Bogotá lacustrine deposit, a site specific calibration of the CPTu was carried out for the parameters related to undrained shear strength and unit weight.

The correlations currently available for the soil unit weight have shown low applicability for the soils of the Bogota lacustrine deposit due to the soft nature of the clays with special structural characteristics, such as the diatom particle content. Therefore, the precision of the parameters dependent on unit weight, such as vertical stresses, have a high degree of uncertainty.

A correlation was generated for the calculation of unit weight based on the variables obtained from the CPTu applicable to the normally and overconsolidated soil of the Bogotá lacustrine deposit. The Nkt factor was calibrated with shear tests results for the first 30 m of the deposit, obtaining a zoning in the parameter with respect to the depth and location in the deposit.

For the overconsolidated layer that exists in the geotechnical soil profile of the study, the cone factor Nkt has an average value equivalent to 14.1. For normally consolidated soft clays identified at depths greater than 10 m, the Nkt factor has an average value of 11.7.

Acknowledgements

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5. References

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