Determination of the undrained shear strength of organic soils using the cone penetration test and Marchetti's flat dilatometer test

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ABSTRACT: In organic soils and peats, the determination of the undrained shear strength is done through the same methods used in mineral soils, however, not all the methodologies can be applied to this type of soils. Organic soils have different degrees of decomposition, different fibre types, and even the presence of gas by decomposition processes. For this reason, a comparison of the determination of this parameter in organic soils, which are present in the South of the City of Quito, in Ecuador, has been carried out through in situ tests such as the Cone Penetration Test (CPT), the Marchetti Dilatometer (DMT) and the Standard Penetration Test (SPT), as well as with laboratory tests. The research concludes with a comparative graphic of the undrained shear strength obtained with each test.

Keywords: Organic soils; Undrained Shear Strength; Marchetti's flat dilatometer; Cone penetration test; Ecuadorian soils.

1. Introduction

The characterization of soft organic soils, which are soil deposits with high water content and plant matter, have been the subject of discussion and concern for engineers for decades [1, 2]. In civil engineering, organic soils and peats are problematic soils, mainly due to the excessive settlements suffered by the structures built on them. This occurs when these soils are subjected to compression stresses, especially in the long term during secondary consolidation [3, 4], presenting axial strains that reach up to 50% due to its considerable compressibility [5].

Their high compressibility, low shear strength resistance and complex distribution of fibers has caused that land with presence of these soils to be avoided in the past for use in construction [6]. Nowadays, due to the increasing urban and industrial development, it is not possible to always avoid this type of soil, which is why it is applied, where possible, the total or partial removal, the use of piles or the application of high safety factors, which can lead to high costs or negative environmental impacts [7, 8].

Due to this need, in order to execute civil engineering works on organic and peat soils in a sustainable way, an adequate mechanical characterization of this type of materials is required, both to estimate their possible short and long-term settlements, as well as to estimate their undrained shear strength, which is necessary for foundation design during and after construction [9]. The characterization of organic soils can be extremely complex [5], and research has been directed towards the estimation of its compressibility, estimation of undrained shear strength, its stabilization and classification [10–16].

Taking into consideration that the undrained shear strength is of great importance for the design of foundations on organic soils, especially when it´s values are considerably low [9], this article will focus on estimating said resistance, through the use of relatively new on-site methodologies for Ecuador, such as the Static Penetration Cone and the Marchetti's Flat Dilatometer, which have already been used for the characterization of organic soils [17–20], as well as the Standard Penetration Test (SPT), which is the most widely used both in Quito and throughout Ecuador, for geotechnical exploration and characterization [21].

The results of these in-situ tests will be compared with laboratory tests, as well as with bibliographic data, in order to determine what type of methodology is applicable and suitable to obtain the undrained shear strength of organic soils.

2. Characteristics of the analyzed site

Organic soils are formed by the deposition of remnants of plants, animals and organisms, which accumulate in areas with little drainage, places with excessive rainfall, such as tropical areas, or sites where low temperatures do not allow aerobic decomposition of these remnants [11, 22]. This phenomenon causes these fragments to accumulate underwater and fossilize [5, 23–27].

Sites with presence of organic soils and mobs can be found in practically all countries of the world [28], their presence being recorded in greater detail in developed countries such as Scotland, with over 60% presence with respect to its total area [29], Finland with 30%, Canada with 18%, Ireland with 17%, Russia and Canada with 10%, and in the United States in 42 states [25, 28, 30]. In the case of developing countries, such as Colombia, Ecuador and Peru, it is only known approximately, with estimates of 0.5 to 5% with respect to its total area [30].

This research was performed on the southern sector of the city of Quito, in the area called *"El Garrochal"*, located 2.5 km north of the *"Saguanchi"* ravine (Figure 1). The city of Quito is in a topographic depression, forming a basin that bears the same name, in an N-S direction. This basin was formed by the activity of the Quito reverse fault system, which has generated a series of elongated hills on the edges of the city [31]. This basin is approximately 30 km long and up to 5 km wide, which is divided into 2 sub-basins, the first one called the central-north sub-basin and the second one called the south sub-basin,

divided by the "*Machángara"* River, and by the dome *"El Panecillo"*[31–33]

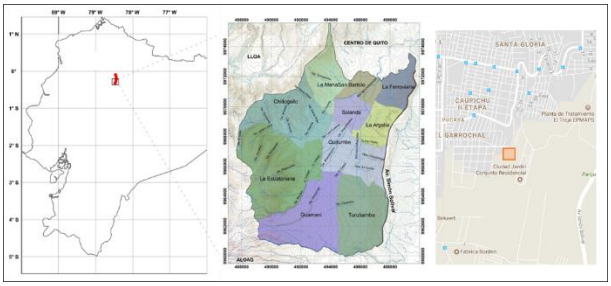

Figure 1. Location of the studied site in Ecuador [33], [34]

The southern sub-basin has an approximate area of 127.7 square kilometers, within which 53.7 kilometers make up the southern valley of Quito, and which is known as "Turubamba" site where the area of *"El Garrochal"* is located. The southern sub-basin is made up of a system of streams that drain towards the *"Machángara"* River to the north, and to the *"Saguanchi"* ravine to the south, with a variable height between 3080 and 2800 meters over the sea level [33]. It is in this area called "Turubamba" where there was previously a lagoon, which during its drainage to the *"Machángara"* River - not being completely drained - left a high water level, with traces of organic material, forming a swampy terrain, being the reason why it was called by the locals "Turubamba", which translates into "Plain of mud" or "Land of Swamps" [35, 36]. This area is currently part of the *"El Pintado"* unit, formed by a set of volcanic gaps interspersed with sandstones and clayey layers whose base is on the "Guamaní" Volcanic-sedimentary unit, which intersect and overlap from north to south from the southern sub-basin. On this set of gaps are layers of clay and green sand, reaching a thickness of 10 meters.

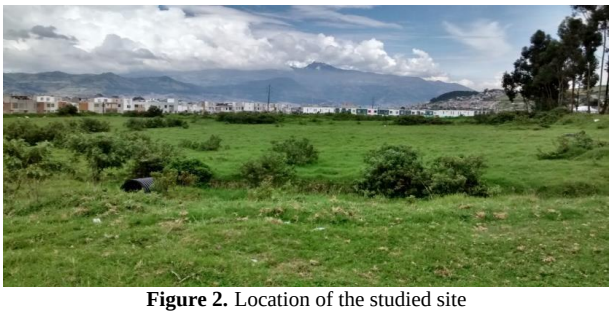

Figure 2. Location of the studied site

Finally there is a series of mobs and organic soils that reach a thickness of 20 meters [33]. It is precisely on this latest series of mobs where housing and public services have been built in recent decades, which have suffered constant problems due to settlements, causing it to be analyzed by the public and private sector, and that is where this research will be executed. (Fig. 2.)

3. Materials and Methodology

The equipment used includes a Cone Penetration Test equipped with a Begemann mechanical cone, a Marchetti Flat Dilatometer – DMT, and the equipment to execute the Standard Penetration Test - SPT. A Tecnotest hydraulic unit with a maximum force of 200 kN was used to drive both measuring equipment on the ground. The tests were carried out at a location in the sector called "El Garrochal", in the South of Quito (Fig. 1), with 3 CPT trials, 3 DMT trials and 3 SPT trials, with a total of 9 in-situ trials carried out. The sites of each trial were separated between 1.5 to 2 meters; The results presented are the average of the values obtained in each of the trials. In SPT drilling, organic soil samples were collected for determination of percentages of organic matter, water content and Unified Soil Classification System tests.

The following parameters were recorded during the execution of the CPT and DMT tests:

- CPT: Measurement of cone tip resistance q_c,, friction resistance of jacket f_s, with data taken every 20 cm for both readings.
- DMT: Measurement of pressures p_0 and p_1 every 20 cm in vertical profiles.

The procedures for performing the aforementioned tests, as well as the geometry of the cone tip, the friction jacket, and the Marchetti flat dilatometer, were executed based on the respective ASTM standards [37, 38].

Based on the information recorded in the field, the following values for the CPT were calculated:

$$q_c = 1000 * Q_c \,/\, A_c \quad (1)$$

Where q_c is the resistance of the cone in MPa, Q_c is the thrust force measured at the tip of the cone (kN) and A_c is the area of the base of the cone, which is equivalent to 1000 mm². The results can be observed in the first 3 schemes of Fig. 3.

$$f_s = 1000 * F_s \,/\, A_s \quad (2)$$

$$F_s = Q_f \,/\, Q_c \quad (3)$$

Where f_s is the resistance of the friction jacket (MPa), F_s is the thrust force measured in the friction sleeve (kN), Q_f is the thrust force measured at the tip of the cone plus the friction sleeve, and A_s is the area of the friction jacket, equivalent to 15000 mm².

$$R_f = 100 * f_s \,/\, q_c \quad (4)$$

Where R_f is the friction ratio, presented as a percentage.

In the case of DMT, the readings A and B are corrected by the stiffness of the membrane to determine the pressures po and p1, which are applied to the ground at the beginning and at the end of the expansion. The following expressions are used:

$$po = A + \Delta A \quad (5)$$

$$p1 = B - \Delta B \quad (6)$$

Where ΔA is the external pressure that must be applied to the outdoor membrane to keep it in contact with its base and ΔB is the internal pressure which inflates the center of the membrane 1.0 mm from its base. The ΔA and ΔB values are measured by a field procedure, which is to apply a vacuum and a pressure on the membrane respectively, and read the values for which the membrane deflates or inflates 1.0 mm [38].

$$\Delta A = 0.15 \pm 0.05\ kg/cm2 \quad (7)$$

$$\Delta B = 0.5 \pm 0.2\ kg/cm2 \quad (8)$$

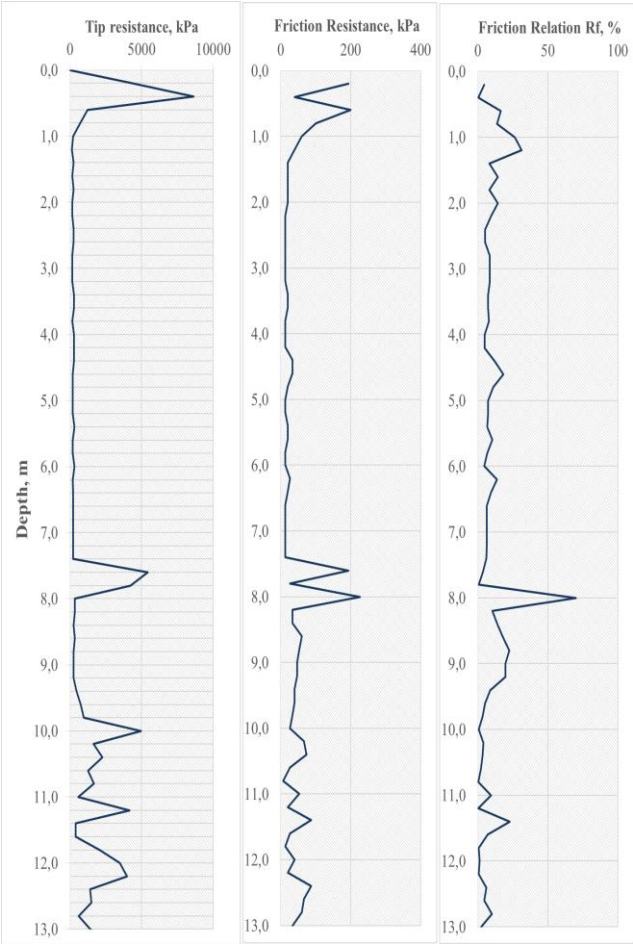

Figure 3. CPT Results

The DMT results are presented as po, p1 versus depth diagrams, and as diagrams of the calculated parameters I_D, KD, and ED as defined below:

- Material Index I_D :
  $$I_D = \frac{\Delta p}{p_o - u_o} \quad (9)$$
- Horizontal Stress Index K_D :
  $$K_D = \frac{p_o - u_o}{\sigma_v} \quad (10)$$
- Dilatometer Modulus E_D:
  $$E_D = 38.2 * \Delta p \quad (11)$$

Where u_o and σ_v are the water pore pressure and vertical effective strength respectively, and must be known, at least approximately, prior to the insertion of the blade. The results can be observed in the 3 schemes of Fig. 5.

In the SPT test, the number of "N" strokes are measured, necessary to introduce the sampler at a depth of 30 cm was determined by means of a 64 kg mass hammer that falls from a height of 76 centimeters, information that can be observed in the stratigraphic profile of Fig. 6. [39]. Of the first 7 meters, where the greatest amount of organic soil was witnessed and up to where altered samples were recovered from the SPT test, organic matter content and Atterberg limits were attempted.

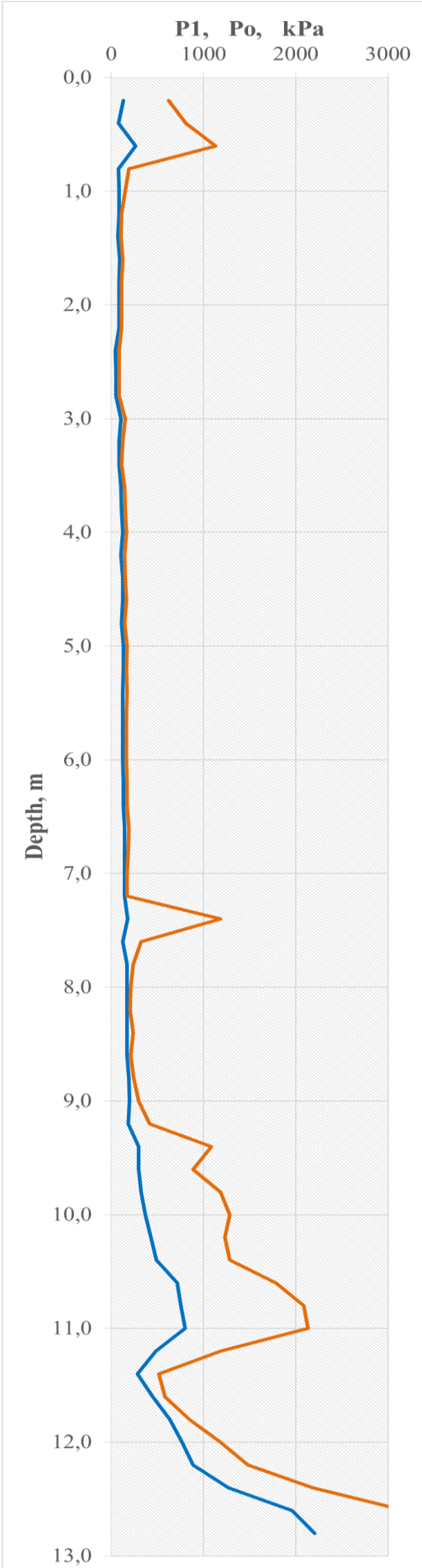

Figure 4. DMT P1 and P0 Results

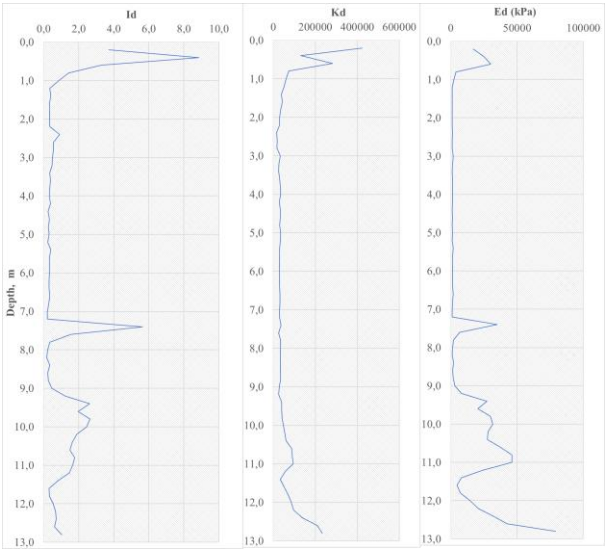

Figure 5. DMT Results

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Table 1. SPT Results

Depth (m)	%w	LL	PL	PI	% Finer N° 4	% Finer N° 200	USCS	N45
0,5	31	42	33	9	100	58	ML	7
1	134	148	92	56	100	68	OH	4
2	202	263	150	113	100	55	OH	1
3	158	123	83	40	100	75	OH	2
4	273	166	103	63	100	81	OH	2
5	387	368	225	143	100	93	OH	3
6	472	335	208	127	100	91	OH	31
7	262	271	165	106	100	85	MH	40
7,5	214	226	141	85	100	74	MH	9

The statistical parameters obtained from both tests are presented in Fig. 10. and 11., corresponding to the resistance to the tip of the cone q_c, and to the DMT Material Index I_D. For the determination of the undrained shear strength, the following expressions were used:

- $Cu_{CPT} = \frac{(q_c - \sigma_{vo})}{N_{KT}} [MPa]$ [40] (12)
- $Cu_{DMT} = 0{,}22 * \sigma_{vo} * (0{,}5 * Kd)^{1{,}25}$ $[MPa]$ [17] (13)
- $Cu_{LAB} = \frac{qu}{2}$ $[MPa]$ (14)

Where: σ_{vo} is the overload pressure at the measured depth [MPa], N_{KT} is an empirical coefficient depending on the type of soil, and qu is the highest resistance obtained from the unconfined compression tests, applying the Tresca model to obtain Su.

In the case of the SPT test, the existing correlations for soft soils were applied, since there were no direct correlations for mobs or organic soils in the existing literature. Below are the equations and tables used for the correlations:

Table 2. Consistency of saturated cohesive soils, N SPT and q_u (kPa) [41]

Consistency	N70 SPT	q_u (kPa)
Very Soft	< 2	< 25
Soft	2 - 4	25 - 50
Medium	4 - 8	50 - 100
Stiff	8 - 15	100 - 200
Very Stiff	15 - 30	200 - 400
Hard	> 30	> 400

Table 3. Consistency of saturated cohesive soils, N SPT and q_u (kPa) [42]

Autors	Soil Type	Su (kPa)
Sanglerat (1972)	Clay	12.5N
	Silty Clay	10N
Terzaghi & Peck (1967)	Fine-grained soil	6.25N
Hara et al. (1974)	Fine-grained soil	$29N_{60}^{0.72}$
Sowers (1979)	Highly plastic soil	12.5N
	Medium plastic clay	7.5N
	Low plastic soil	3.75N
Nixon (1982)	Clay	12N
Sivrikaya & Toğrol (2002)	Highly plastic soil	$6.82N_{60}$
	Low plastic soil	$4.93N_{60}$
	Fine-grained soil	$6.18N_{60}$
Stroud (1974)	PI < 20	(6-7)N
	20 < PI < 30	(4-5)N
	PI > 30	4.2N
Décourt (1990)	Clay	$15N_{60}$
Ajayi & Balogun (1988)	Fine-grained soil	1.39N+74.2
Hettiarachchi & Brown (2009)	Fine-grained soil	$4.1N_{60}$
Sirvikaya (2009)	UCS Test	Su = 2.41N – 0.82wn + 0.14LL + 1.44PI

For the determination of Su by correlations with the SPT N, all correlations were applied, and if necessary, a possible correlation was sought with the results obtained by laboratory (unconfined compression tests), whose results are presented in the next section.

4. *Results*

The studied soils have an average organic content of 26.89%, which according to the Landva classification system [43], are classified as organic soils, and a moisture content of 269.7% in the first 7 meters prospected. Both contents were obtained by the procedure recommended by ASTM D2974-14 "Tests for determination of moisture, ash and organic matter of peats", where a temperature of 110 ° C was maintained until there is no mass change, which took 24 hours, to subsequently apply 440 ° C until there is no mass change, which took 7 hours.

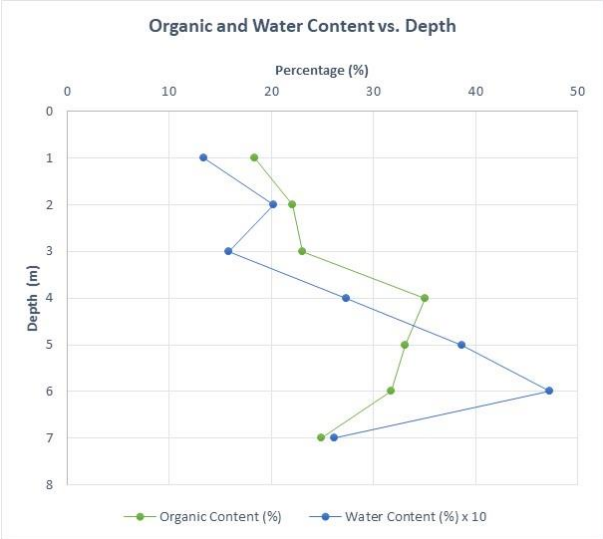

Figure 6. Organic and Water Content vs Depth

Prior to the application of this methodology, other methods for the determination of organic matter were studied [43–45], which is close to the methodology presented by Landva et. al, 2007 [46], where it is proposed to apply 440 ° C for five hours to determine the content of organic matter.

The results are presented in Fig. 6., where the moisture content was divided by ten so that it can be compared with the organic content. Without taking into account the fifth and sixth meter of depth, due to the presence of sands that reduced the amount of organic matter, it can be observed that both contents have a close relationship in their variation, with differences in average of 4.1%. Similar relationships have been previously investigated obtaining a a comparable behavior [47], which can be very useful when there are no measures of this parameters in the field or in the laboratory [48], as well as the complicated that can be a stratigraphy, where there are many variations in the types of material, such as the 5th and 6th meter depth, the relationship between both contents may be of little use [49].

On these samples the Atterberg limits were determined (Fig. 7), which are indicators of the ranges of moisture content in which the consistency of a soil passes from a liquid state, to plastic and finally to solid state [41].

In the case of organic soils and mobs, their determination has been studied as complicated, reporting erratic and complicated interpretation values [45, 50, 51],

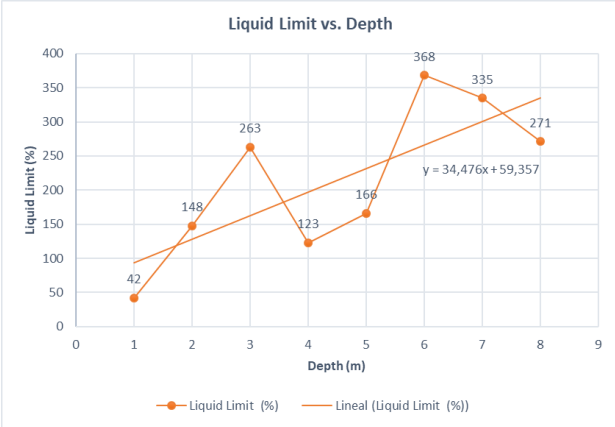

Figure 7. Liquid Limit vs Depth

and in other cases, it is recommended not to use the Atterberg limits for this type of soil [15]. However, the limits tests were carried out, and the estimation of organic content based on the liquid limit was also calculated, using the Skempton equation:

$$(LL - 50) = 5 * N \quad (15)$$

Where N = Organic Content [45], whose results can be seen in Fig. 8., and which do not keep a correlation, sharing an approximation only to the values of organic matter in the third and fourth meter of depth.

The readings obtained from the CPT and DMT tests were plotted on the soil type prediction nomograms that usually apply [52, 53], which can be observed in the Figs. 11 and 13 respectively.

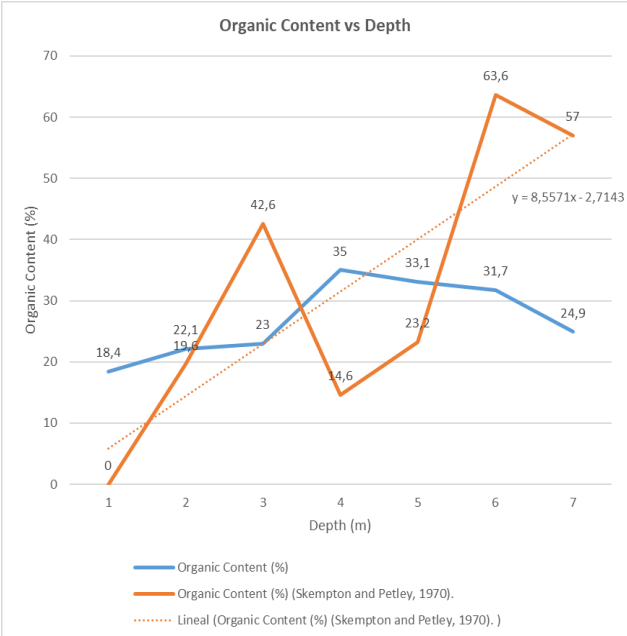

Figure 8. Organic Content with LL Correlations vs Depth

From the results obtained from the CPT test presented in Fig. 3., the statistics presented in Fig. 9. were obtained, where the resistance to the tip less than 1300 kPa represents 73% of the total data. From the same results, the nomogram proposed by Robertson and Campanella [53] was applied, with a greater extension in the horizontal axis, due to the fact that this soils have Friction Ratio values that reach up to 150%. The application of this nomogram gave results of soil types different from

those currently found, presenting more than 70% of the Ratio values that reach up to 150%. The application of this nomogram gave results of soil types different from those currently found, presenting more than 70% of the soils as mineral soils, so, in the case of organic soils, the use of Robertson's nomogram can give results of incorrect characterization in about 70%, and those that are correctly characterized, with FR friction ratio values well above 8% delimited by the original nomogram.

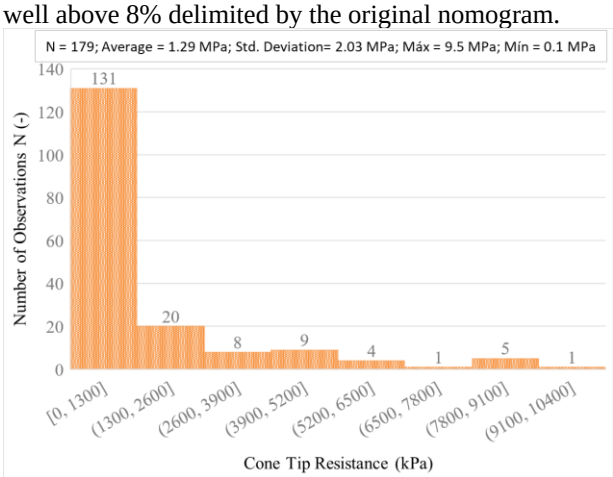

Figure 9. Cone Tip Resistance – Number of Observations

From the results obtained from the DMT test of Figure No. 5, the statistics presented in Figure No. 11 were obtained, where material index values lower than 1.26 represent 75% of the total. From the same results, the nomogram proposed by Marchetti and Crapps [52] and presented in the ASTM standard [38] was applied, which can be seen in Fig. 10., where it was obtained that 18% of the points were classified as organic soils or mobs, 45% presented points close to those classified as mobs, however they were classified as clays, and the remaining 55% as mineral soils in general.

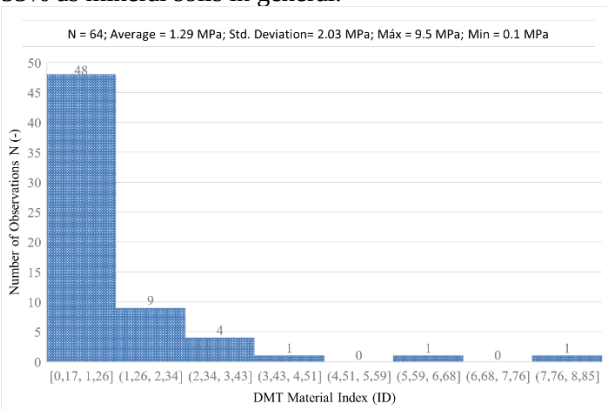

Figure 10. Organic and Water Content vs Depth

Considering the obtaining of data from both the CPT and DMT test, a correlation between the resistance of the CPT cone, qc, with the oedometric module M_{DMT}, based on the general formula that allows both $M_{DMT} = \alpha * qc$ (16) to be correlated. In Fig. 13 a linear trend line can be observed where a value of $\alpha = 9.92$ is obtained, which was obtained with data only up to 12.8 meters deep, since there is a very high variability at greater depth, for which a value of $\alpha = 9.9$ is proposed for the present studied soils.

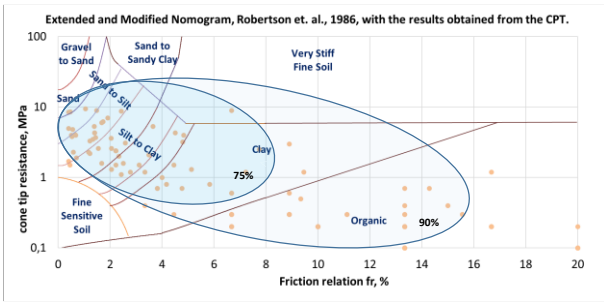

Figure 11. Extended and Modified Nomogram [40]

Finally, the equations were applied to obtain the resistance to the undrained cut Cu indicated in the Methodology, from which the comparative table indicated in Fig. 18. was obtained, with ranges of Cu up to 300 kPa. A clear similarity of values is observed between the results of the DMT, CPT and Laboratory tests, whose Cu ranges do not exceed 40 kPa and are shaded from the first to the ninth prospecting meter, which is where the organic soil concentration was presented .

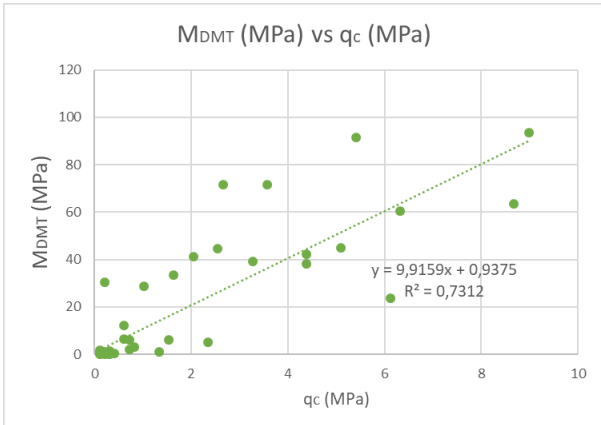

Figure 12. M_{DMT} vs qc (MPa)

Fig. 20 shows a clear over estimate of the value of Su by means of the SPT test in the entire prospected depth, with a clear example in the third prospecting meter, where the ranges of laboratory test trials range from 7 at 25 kPa, from the CPT test from 9 to 26 kPa, and from the DMT test from 5 to 11 kPa, while with the SPT test a value of 47.8 kPa is obtained, which represents on average an increase of 300% of the estimated value of Cu with respect to the other trials. In the sixth and seventh meters this increase in the Cu estimate reaches values higher than 2500% with respect to the values estimated with the CPT and the DMT.

The values of undrained cut resistance (Su) in the laboratory were obtained by means of simple unconfined compression tests, where the Tresca criteria $Cu_{LAB} = \frac{qu}{2}$ (17) was applied. The laboratory results are as shown in Fig. 14 to 17.

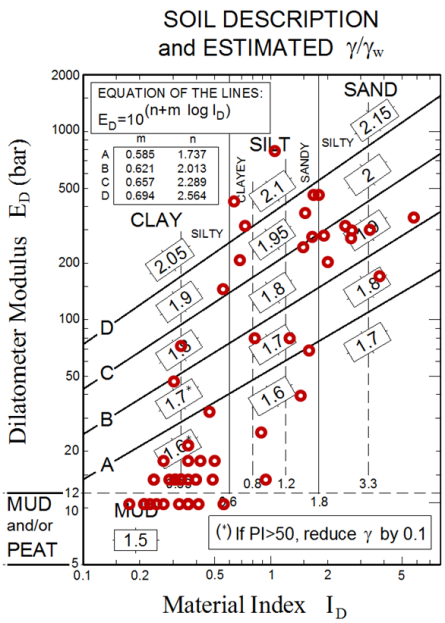

Figure 13. Material Index vs Dilatometer Modulus [52]

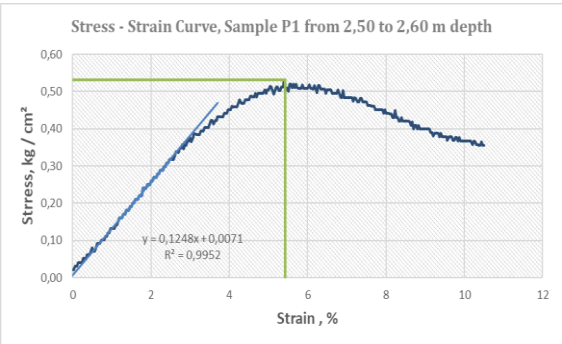

Figure 14. Stress Strain Curve, Sample P1 from 2,50 to 2,60 m

$$\boldsymbol{Cu_{LAB}} = \frac{qu}{2} = \frac{0.53}{2}\,[kg/cm2]=0.265\,[kg/cm2] = \mathbf{25.99}\,[\boldsymbol{kPa}]$$

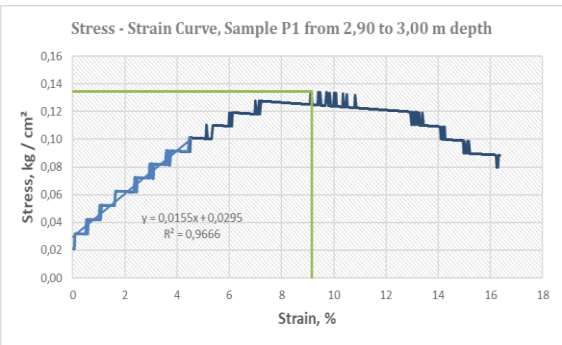

Figure 15. Stress Strain Curve, Sample P1 from 2,90 to 3,00 m

$$\boldsymbol{Cu_{LAB}} = \frac{qu}{2} = \frac{0.13}{2}\,[kg/cm2]=0.065\,[kg/cm2] = \mathbf{6.37}\,[\boldsymbol{kPa}]$$

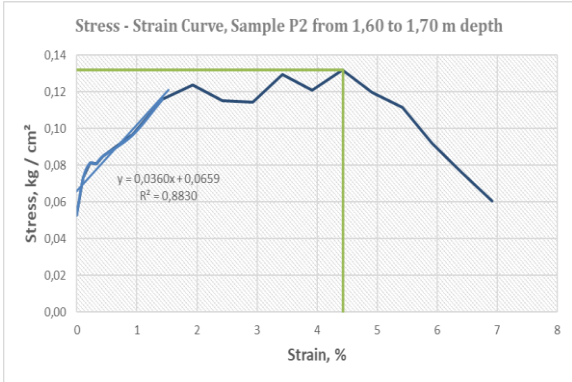

Figure 16. Stress Strain Curve, Sample P2 from 1,60 to 1,70 m

$$\boldsymbol{Cu_{LAB}} = \frac{qu}{2} = \frac{0.13}{2}\,[kg/cm2]=0.065\,[kg/cm2] = \mathbf{6.37}\,[\boldsymbol{kPa}]$$

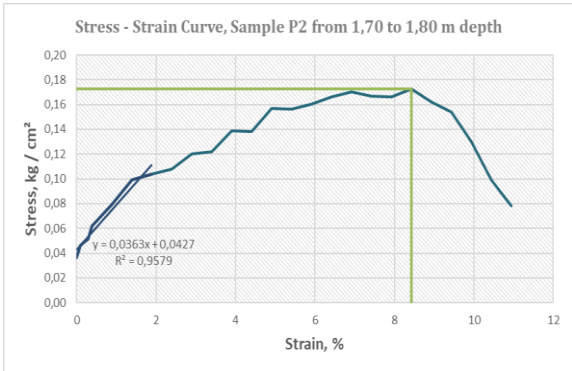

Figure 17. Stress Strain Curve, Sample P2 from 1,70 to 1,80 m

$$Cu_{LAB} = \frac{qu}{2} = \frac{0.17}{2}\,[kg/cm2]=0.085\,[kg/cm2] = \mathbf{8.34}\,[\boldsymbol{kPa}]$$

The laboratory results were initially compared with the correlations between the N SPT and Su (kPa) for fine soils [42], obtaining the graph presented below:

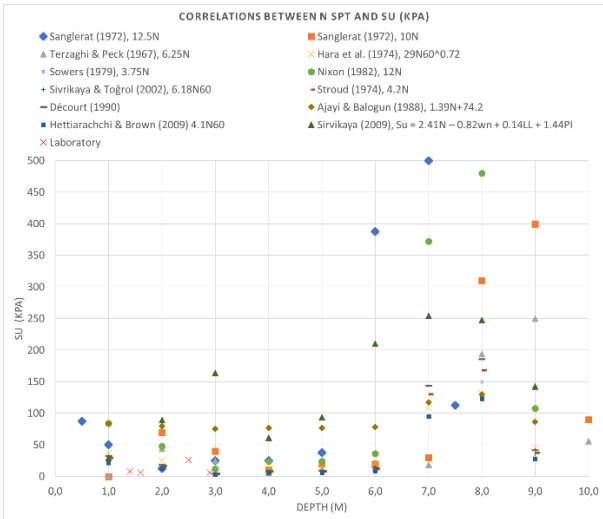

Figure 18. Correlations between N SPT and Su 0-500 kPa

The values have a high dispersion, with ranges from 4 to 500 kPa in the 7.5 meters surveyed. In order to compare with the results obtained in the laboratory, the Y axis is modified to analyze the values between 0 and 50 kPa:

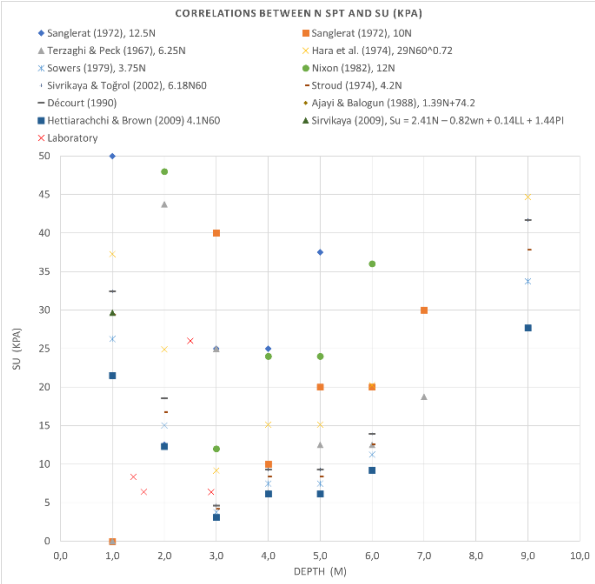

Figure 19. Correlations between N SPT and Su, 0-50 kPa

In an analysis of the results presented in a range of 0 to 50 kPa (Fig. 20.), it can be seen that the results of 5 to 25 kPa keep a close approximation, especially over the range of 7 to 12 kPa, where the Dilatometer obtains the most conservative results in general, and the average CPT values result in the values closest to those obtained with laboratory tests. The analysis of these results will be presented and discussed in the next chapter.

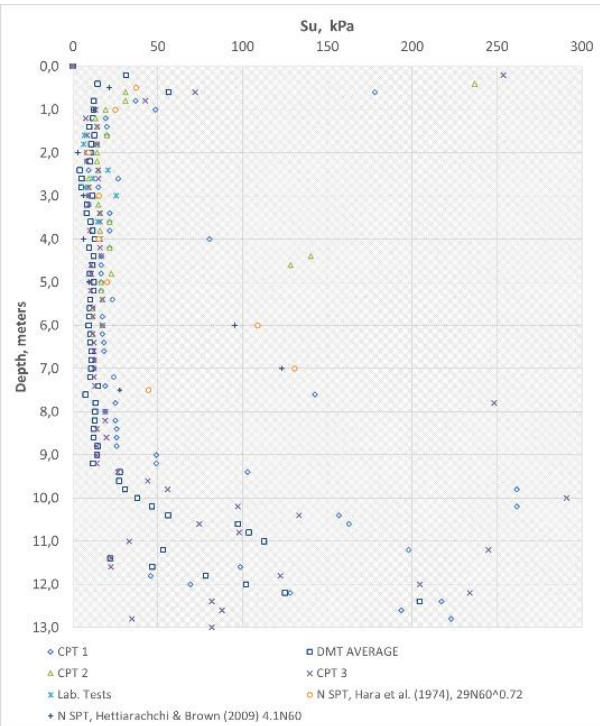

Figure 20. Su (kPa) vs Depth (m), 0-300 kPa

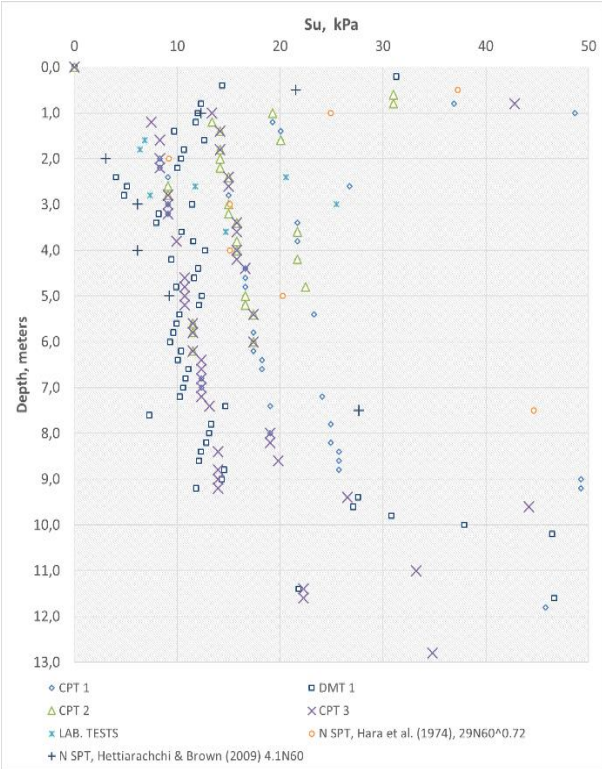

Figure 21. Su (kPa) vs Depth (m), 0-50 kPa

5. *Discussion and Conclusions*

In the determination of the organic content and humidity, a relationship was observed between the increase or decrease of both parameters, which confirms the existing conclusions in related research, where similar behaviors were found [54]. However, in the prospected depth it was observed that the relationship is affected in the fifth and sixth meters, where there are layers of sand interspersed with organic soils, which can serve as drains and affect the aforementioned relationship. The presence of mineral soils can modify any possible correlation, and in previous research it has been found that depending on the site, the moisture content may not be of any use to determine the organic content or characterize these soils [49]. It is important to mention that, due to the fragility and open structure of organic soils and mobs, the moisture content measured in the laboratory may not be the same as the moisture content in situ.

With the altered samples obtained through the SPT test, Atterberg boundary tests were carried out, which presented complexity due to the presence of the organic matter itself. The results obtained were erratic, with a tendency towards an average value between 25 and 30% of organic content. These results were used to apply the Skempton and Petley equation [45], which correlates the results obtained between the organic content and the liquidity limit, however, no similarity was observed between the results, when presenting a tendency to increase liquid limits and therefore organic content as a function of depth, with an average slope of 8.5, so it is concluded that this equation is not applicable for the present soils, being only applicable for the soils where it was studied . Recent research [15] concludes that, unlike

mineral soils, Atterberg boundaries are not a reliable source for determining the consistency of organic soils, as well as having no acceptable correlation with geomechanical properties, which can relate with the erratic data from Liquid Limits obtained in this investigation.

Organic soils, when represented in the nomograms of CPT [40] and DMT [52], behave like mineral soils, being classified as silty sands, silts, clay silts and clays in more than the 70%. In order to locate the points, it was necessary to modify Robertson's nomogram due to the high values of the Friction coefficient (Fig. 11.). Similar results have been obtained previously [20], where it was shown that none of the nomograms presented for both the DMT and the CPT, serve to classify organic soils adequately, and which reflects the complex nature of these soils, both for their classification and for their mechanical characterization.

Obtaining the Cu values in each of the trials was performed based on the equations available in the literature, where it is observed that, throughout the entire depth, the DMT provides the lowest values, which can be explained as the dilation of the membrane is lateral, coinciding with the potential orientation of the fibers and eliminating any possible reinforcement of them. On the other hand, with the CPT, the closest proximity to the Cu values obtained in the laboratory was achieved, which may be due to the way in which the test is performed, where a vertical compression is simulated, which allows horizontal oriented fibers to tighten creating a reinforcement similar to a geotextile. Data obtained through the DMT carried out in Poland in mobs [55], yield results almost identical to the DMT tested in Ecuador, which may be due to safety factors that Marchetti applied in its correlation [52].

Considering that in Ecuador the main test for on-site characterization is the SPT, it was executed, taking advantage of obtaining the altered samples for the classification tests. Correlations of the SPT N with Su (or Cu) are non-existent for organic soils in the literature, so several equations for fine soils were applied [42]. The results indicate that there is no correlation that fits all laboratory samples, an example being the points at 2.50 and at 2.90 meters deep, where the undrained shear strength varies between 26 kPa to 6.37 kPa respectively in 40 centimeters, variation that is not detected by the SPT N. From the graphs it is observed that it is not possible to obtain a direct correlation between the SPT N and the Su in organic soils, possibly due to the variable decomposition, type and orientation of the organic matter, as well as the heterogeneous deposition of materials in areas with presence of mobs and organic soils. However, results are obtained close to the correlation proposed by Hettiarachchi & Brown (2009) [56], which is presented in the comparative Figs. 18 and 19. Because it is not the scope of this research, it is recommended that this conclusion to be verified. with a greater quantity of samples and data in future investigations.

When obtaining close values of Su between the CPT and DMT tests, a correlation between the resistance of the CPT cone, q_c, was plotted with the M_{DMT} oedometric module, based on the general formula that allows both $M_{DMT} = \alpha * q_c$ to be correlated to which obtained a value of $\alpha = 9.2$. Similar correlations have already been executed, obtaining values $\alpha = 6.0$ for organic soils and pre-consolidated peat with organic contents of 50 to 92% [20]. The difference in organic content between the soils studied (about 50% on average) could explain the difference of 3.2 in the value of α, which has been seen to reach valus of 8.41 in investigations with over consoldiated sands [57]. It is concluded that the value of α proposed should be studied further, and investigations with a greater spectrum of data should be performed to verify this value.

The research field of field test methods such as the Static Penetration Cone and the Marchetti Dilatometer in our country has not yet been studied, so its advantages and limitations in various types of soils must be investigated for the benefit of our society.

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