Geotechnical parameters for consolidation practice in soft soils in São Paulo region

Antônio Sérgio De Pietro Damasco Penna
Damasco Penna Geotechnical Engineering, Barueri, Brazil, penna@damascopenna.com.br

Fernando Damasco Penna, Érica Sayuri Varicoda Makyama, Luis Antonio Bandeira Neto
Damasco Penna Geotechnical Engineering, Barueri, Brazil, fernando@damascopenna.com.br, erica@damascopenna.com.br, luis@damascopenna.com.br

ABSTRACT: The need to study soft soils increases, as it continuously demanded by urban occupation today. Parameters related to resistance, compressibility, stress history and consolidation properties from these soils are essential for a good geotechnical design, mainly in regions with the occurrence of high compressible saturated soils. Despite the reliability of soil laboratory tests, these can take a long time to give results and usually there are not enough samples to consider them representative. In-situ tests such as CPTU and Vane Test, besides providing highly accurate soil parameters are also interesting due to the ease and agility of field execution and data processing. In this paper, some sites near São Paulo city in Brazil are presented, with data obtained from field and laboratory tests, done initially to develop consolidation projects, with the purpose of enable the usage of floor slab foundations for large and heavy storage buildings. The data obtained from the field and laboratory tests are compared to each other and with relations established by traditional correlations and recommendations for those soils.

Keywords: laboratory tests; in situ tests; clays; undrained shear strength; pre-consolidation pressure

1. Introduction

Geotechnical engineers often want to estimate parameters of resistance, deformability, stress history and consolidation of soils as part of the characterization process.

The undrained shear strength and pre-consolidation pressure are important parameters of high compressible saturated soils to develop foundation, soil reinforcement, soil consolidation designs and there are different ways to obtain them.

Laboratory tests require drilling and undisturbed sampling and can provide great accuracy results. However, they can take a long time to be completed and it is needed many samples of soils to be representative.

While in situ tests are fast at execution and data processing, besides providing parameters along the entire depth tested in Piezocone Penetration Tests (CPTU) and in different previous planned depths in Vane Tests (VT).

The aim of the study is presenting correlations between laboratory and in situ tests, which results were adequate for five different soft, compressible and saturated clays of São Paulo region in Brazil.

2. Laboratory tests

Triaxial compression test (TCT) and consolidation test (CT) are executed into cylindrical undisturbed and remolded soil samples and can be representative if collected many samples of soil in different depths and at different locations of an occurrence area of soft saturated clays.

2.1. Triaxial compression test (TCT)

Undrained shear strength (S_u) is directly obtained from unconsolidated-undrained triaxial compression test (UU test), which do not count with drainage and consolidation of the specimen. This parameter is used regularly in geotechnical stability analyses of situations that fast loads are applied on soft clays and there is not sufficient time for pore pressure to dissipate, so the S_u represent the soil shear resistance and consolidation occur during the loading period.

In the development of this work, TCT tests there are presented were UU tests.

2.2. Consolidation test (CT)

The pre-consolidation pressure (σ'_p) is obtained in consolidation tests and provides information about stress history of soil, its deformability and permeability parameters are directly obtained from consolidation test. This type of test can take a long time to be completed because the deformation process can run slowly due to the low permeability of compressible saturated clays.

3. In situ tests

Unlike the laboratory tests, in piezocone penetration test (CPTU) and vane test (VT) samples are not collected and they can be executed quite fast, acquiring data in the site and providing a complete characterization of the soil.

3.1. Piezocone penetration test

CPTU is internationally recognized as a routine and cost-effective tool for soil profiling and characterization, besides providing constitutive properties of materials.

The piezocone test consists of pushing a tip into the soil at a constant rate and producing a continues profile of soil data, measuring tip resistance (q_c), sleeve friction (f_s) and pore pressure during penetration (u).

As samples are not collected in this type of test, soils characterization is done by theirs behavior type.

Undrained shear strength (S_u) and pre-consolidation pressure (σ'_p) of clays are indirectly obtained from Piezocone Penetration Tests (CPTU).

3.2. Vane test

VT are used primarily to determine undrained shear strength (S_u) of saturated clay deposits and can also be used to obtain the pre-consolidation pressure (σ'_p) indirectly.

The vane test consists of pushing four rectangular blades into the ground to the desired depth, followed by the measurement of the torque required to produce rotation of the blades and, consequently, the shearing of the soil.

This type of test is not applicable to highly permeable soils because it is necessary to guarantee the undrained condition during the execution of the test. This makes the VT ideal for testing soft clays.

4. Investigated Sites

The sites presented and analyzed in this study are located in the surroundings of the city of São Paulo (Brazil). The specific locations of the eight sites are presented in Figure 1.

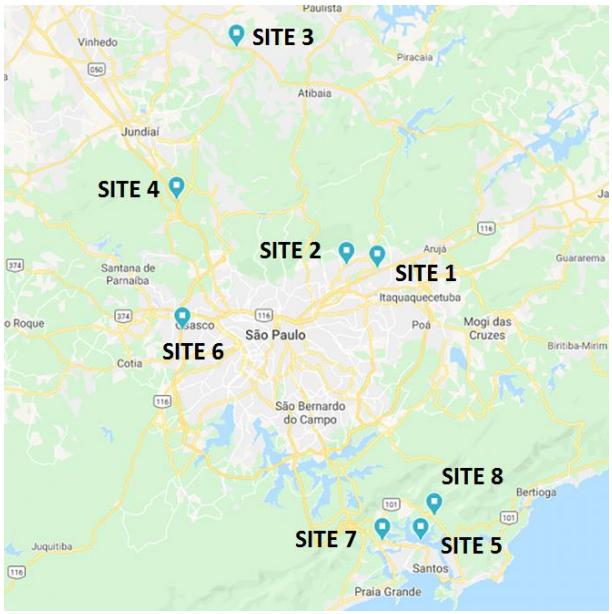

Figure 1. Location map of the studied sites

The sites are described in items 4.1 to 4.8

4.1. Site 1 – Guarulhos

The site number one is located close to the Presidente Dutra Highway and the International Airpoirt of Guarulhos, in the metropolitan area of São Paulo.

In this site, CPTU and VT tests were executed, and undisturbed soil samples were collected with a Shelby tube sampler. Triaxial compression tests (TCT) and consolidations tests (CT) were executed with the samples.

The results of the tests are shown in Figures 2 to 5 and Tables 1 to 2.

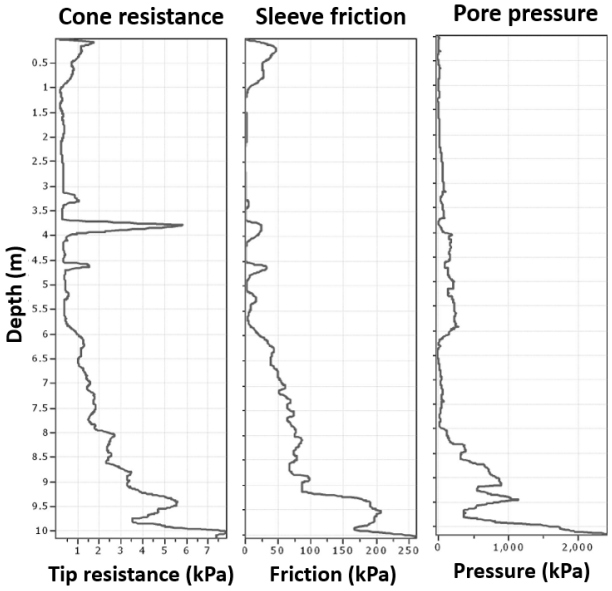

Figure 2. CPTU results from site 1 – Test number: CPTU-01

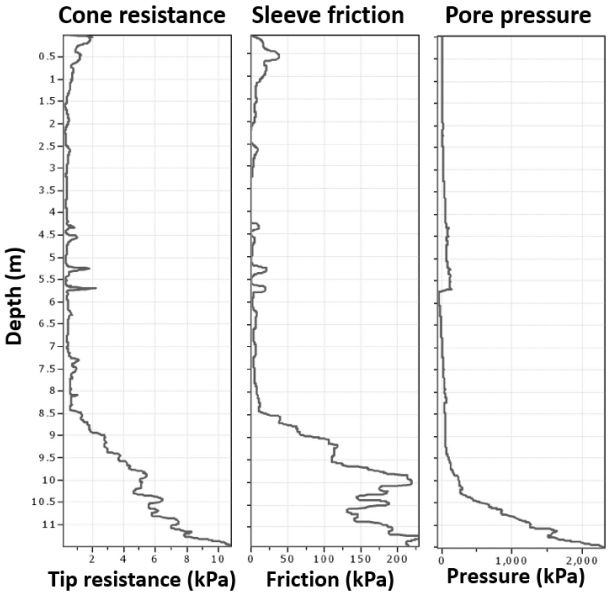

Figure 3. CPTU results from site 1 – Test number: CPTU-02

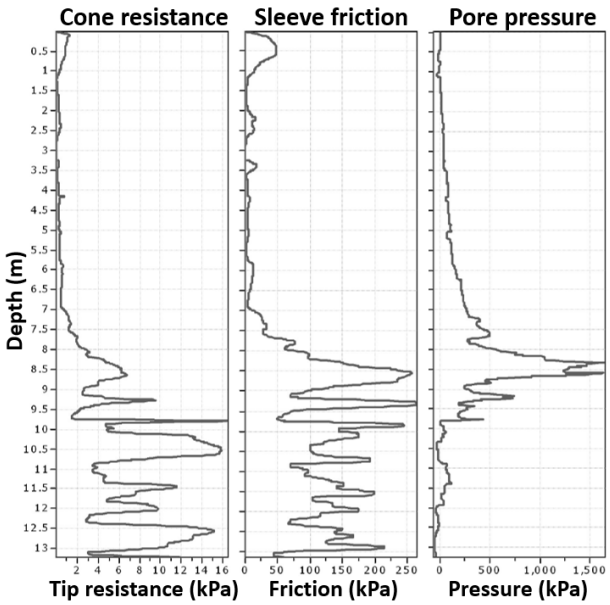

Figure 4. CPTU results from site 1 – Test number: CPTU-03

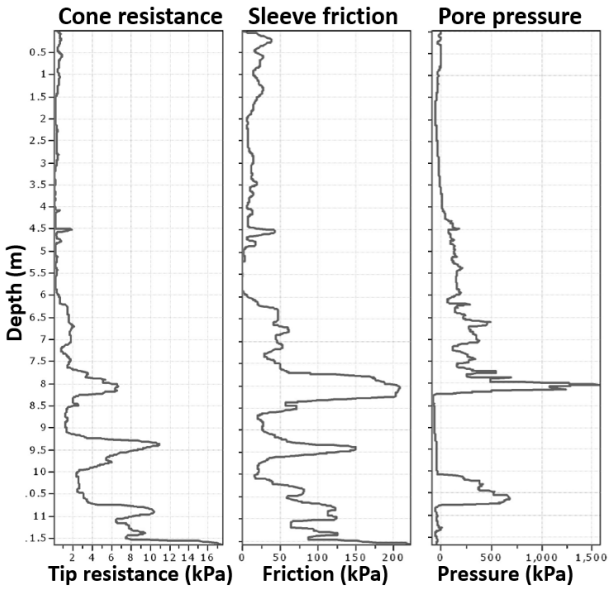

Figure 5. CPTU results from site 1 – Test number: CPTU-04

Table 1. VT test results from site 1

Test number	Depth (m)	Su peak (kPa)	Su remolded (kPa)
VT-01	3,50	13,05	6,45
VT-01	3,80	16,15	8,02
VT-02	4,50	12,75	6,59
VT-03	4,00	30,46	8,36

Table 2. TCT and CT tests results from site 1

Sample	S_u results from TCT tests (kPa)	σ_a results from CT tests (kPa)
Shelby 1	14,79	62,00
Shelby 2	21,08	57,00
Shelby 3	13,76	60,00
Shelby 4	15,77	48,00

4.2. Site 2 – Guarulhos

The site number two is located less than 7 km far from site number one, also close to the International Airpoirt of Guarulhos, in the metropolitan area of São Paulo.

In this site, CPTU and VT tests were executed, and undisturbed soil samples were collected with a Shelby tube sampler. Triaxial compression tests (TCT) and consolidations tests (CT) were executed with the samples.

The results of the tests are presented from the Figures 6 to 16 and Tables 3 to 4.

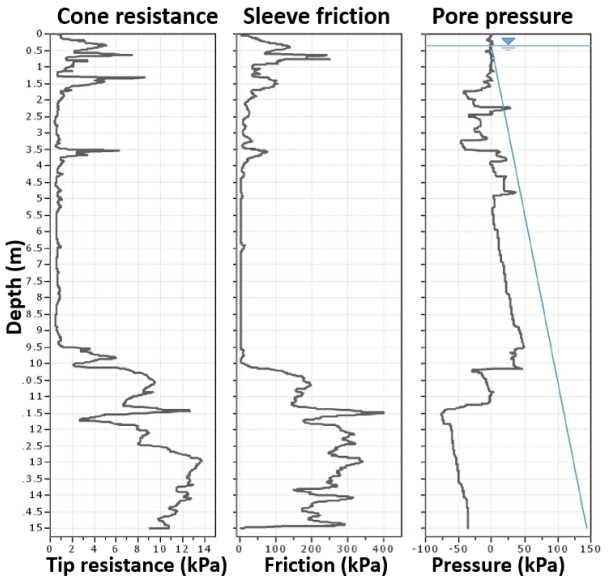

Figure 6. CPTU results from site 2 – Test number: CPTU-01

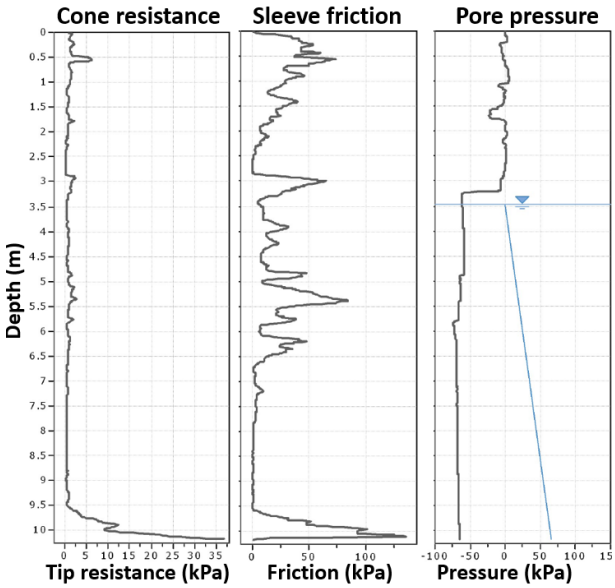

Figure 7. CPTU results from site 2 – Test number: CPTU-06

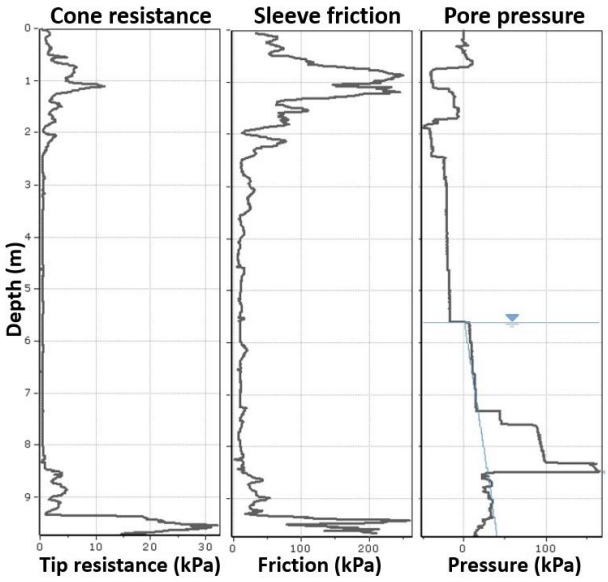

Figure 8. CPTU results from site 2 – Test number: CPTU-301

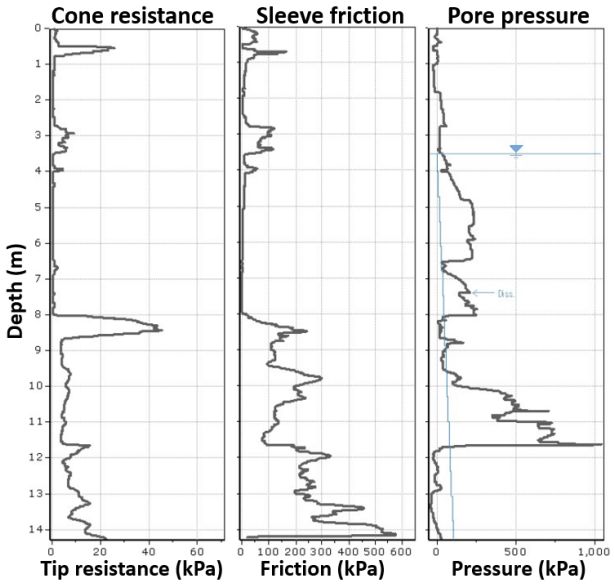

Figure 9. CPTU results from site 2 – Test number: CPTU-302

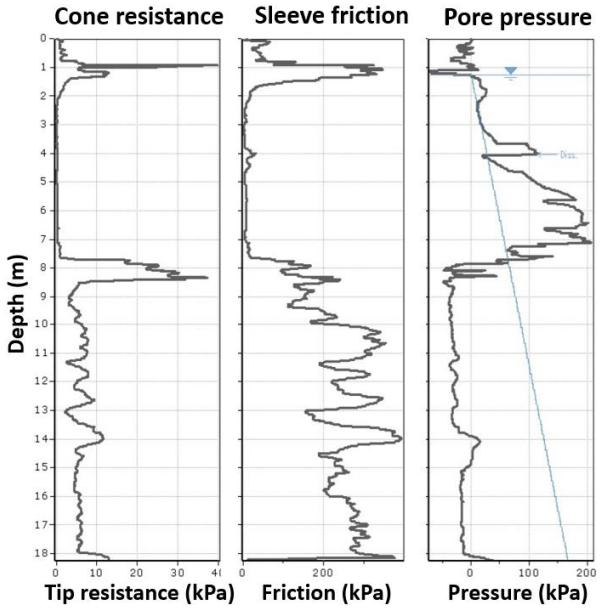

Figure 10. CPTU results from site 2 – Test number: CPTU-303

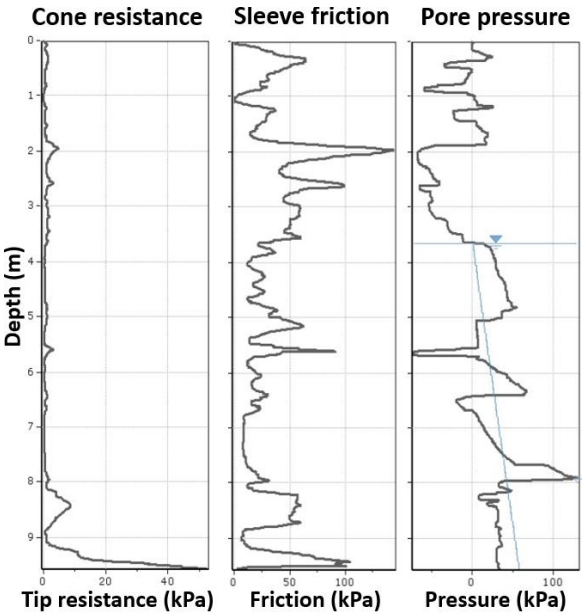

Figure 11. CPTU results from site 2 – Test number: CPTU-304

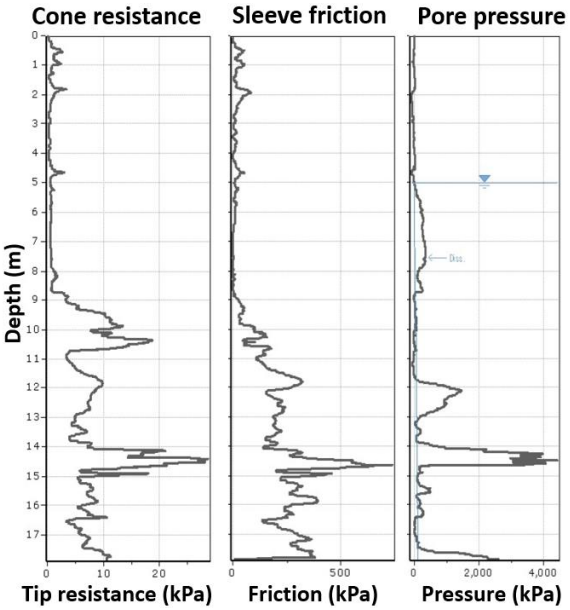

Figure 12. CPTU results from site 2 – Test number: CPTU-305

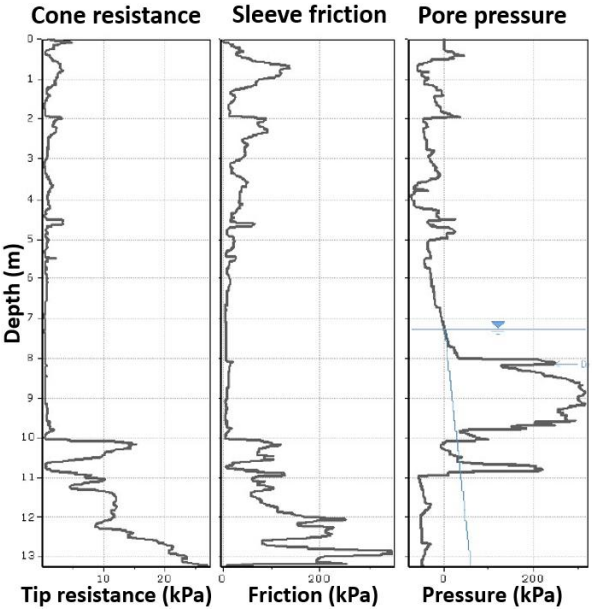

Figure 13. CPTU results from site 2 – Test number: CPTU-306

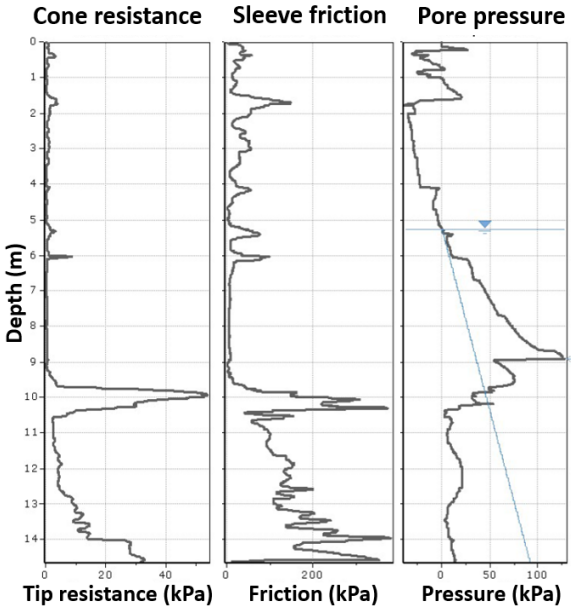

Figure 14. CPTU results from site 2 – Test number: CPTU-308

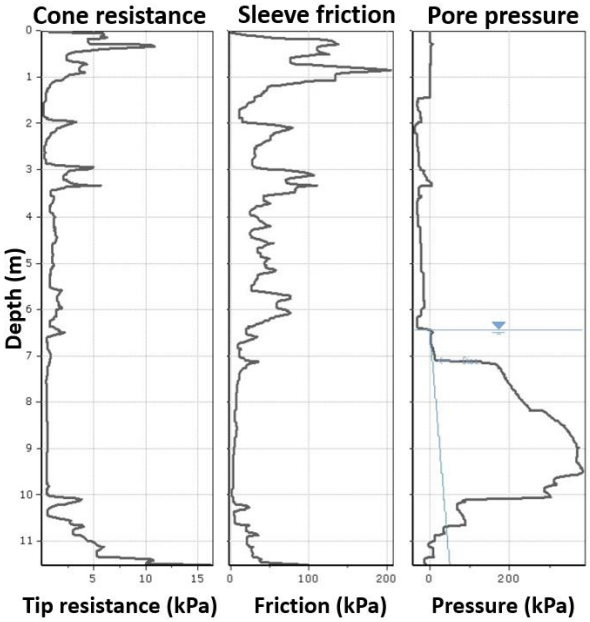

Figure 15. CPTU results from site 2 – Test number: CPTU-502

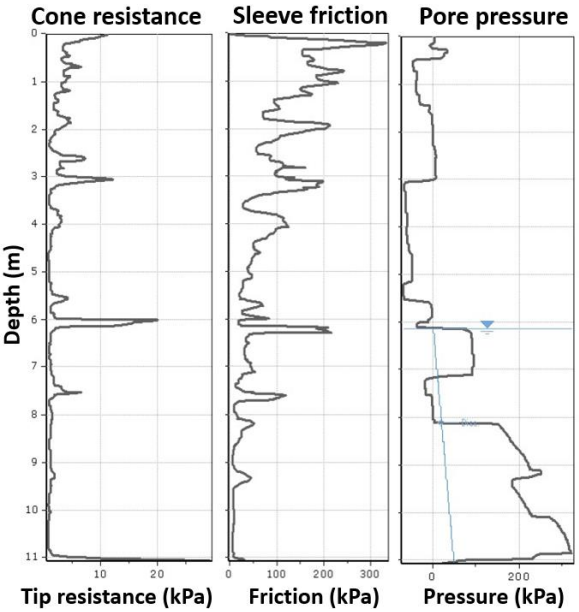

Figure 16. CPTU results from site 2 – Test number: CPTU-503

Table 3. VT test results from site 2

Test number	Depth (m)	Su peak (kPa)	Su remolded (kPa)
VT-301	5,00	39,12	5,60
VT-301	6,00	37,11	8,42
VT-301	7,50	84,15	13,24
VT-302	4,50	80,67	6,27
VT-302	5,50	35,23	9,08
VT-302	6,50	24,25	6,96
VT-303	6,00	45,31	13,39
VT-303	7,00	44,29	13,43
VT-303	8,00	38,74	8,60
VT-304	6,50	27,41	10,82
VT-304	7,50	30,57	18,50
VT-304	9,00	23,72	7,31

Table 4. TCT and CT tests results from site 2

Sample	S_u results from TCT tests (kPa)	σ_a results from CT tests (kPa)
SH-01	NONE	150,00
SH-03	NONE	120,00
SH-301	34,35	110,00
SH-302	40,20	120,00
SH-303	30,20	25,00
SH-304	34,83	140,00
SH-401	19,33	160,00
SH-402	22,83	170,00

4.3. Site 3 – Jarinu

The site number three is located in the city of Jarinu, 60 km distant from São Paulo city, close to Dom Pedro I highway.

In this site, CPTU tests were executed, and undisturbed soil samples were collected with a Shelby tube sampler. Triaxial compression tests (TCT) and consolidations tests (CT) were executed with the samples.

The results of the tests are presented from the Figures 17 to 22 and Table 5.

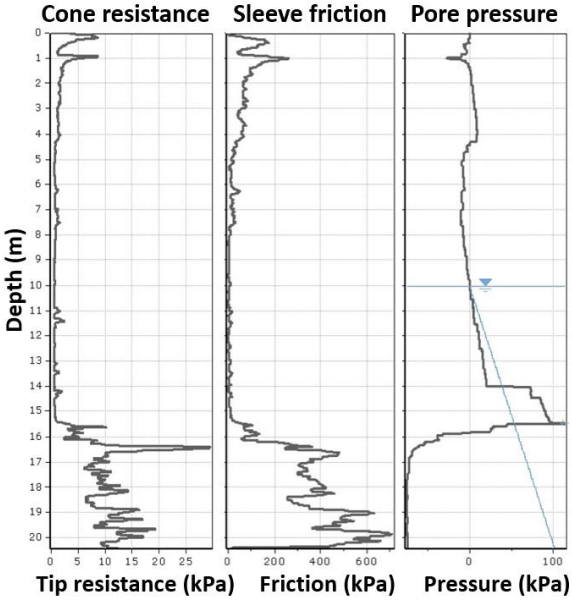

Figure 17. CPTU results from site 3 – Test number: CPTU-02

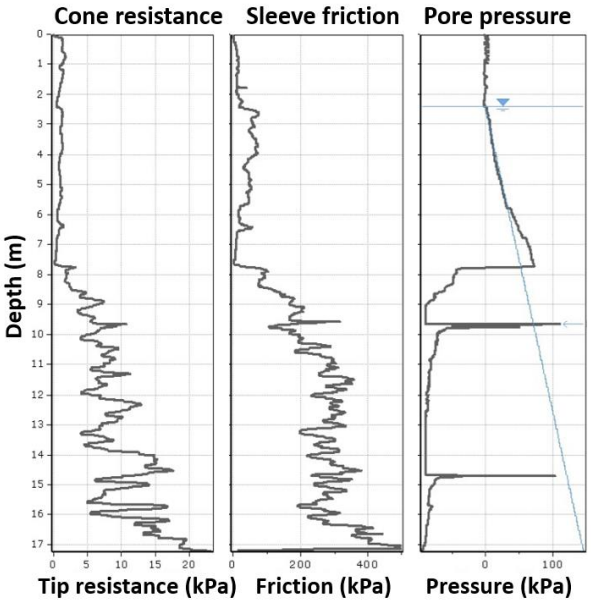

Figure 18. CPTU results from site 3 – Test number: CPTU-03

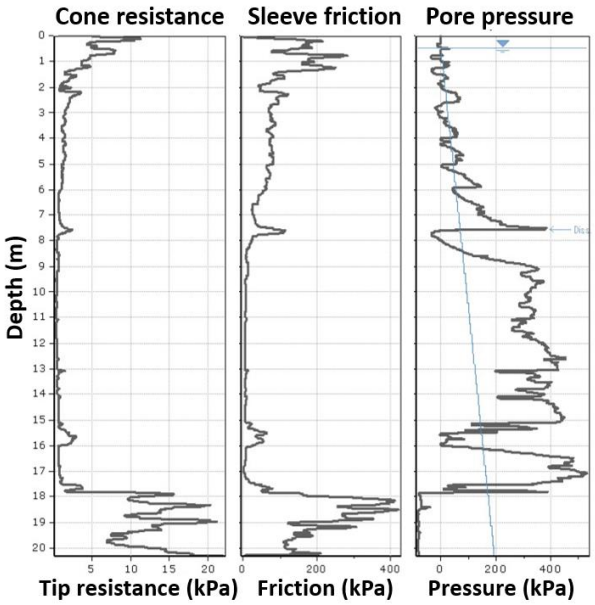

Figure 19. CPTU results from site 3 – Test number: CPTU-04

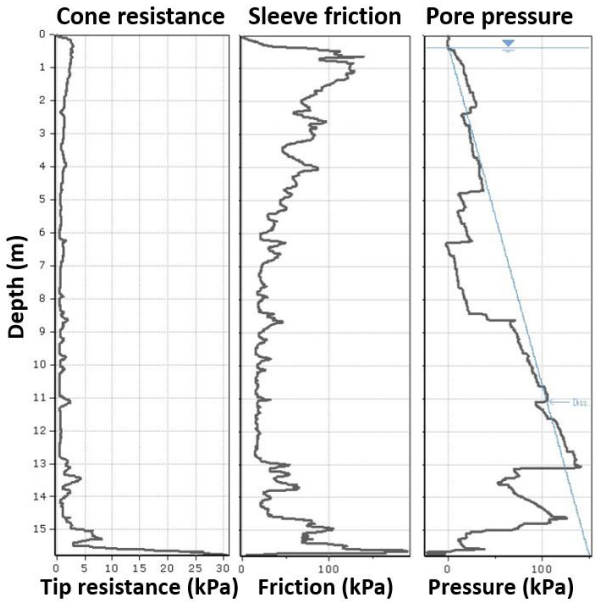

Figure 20. CPTU results from site 3 – Test number: CPTU-06

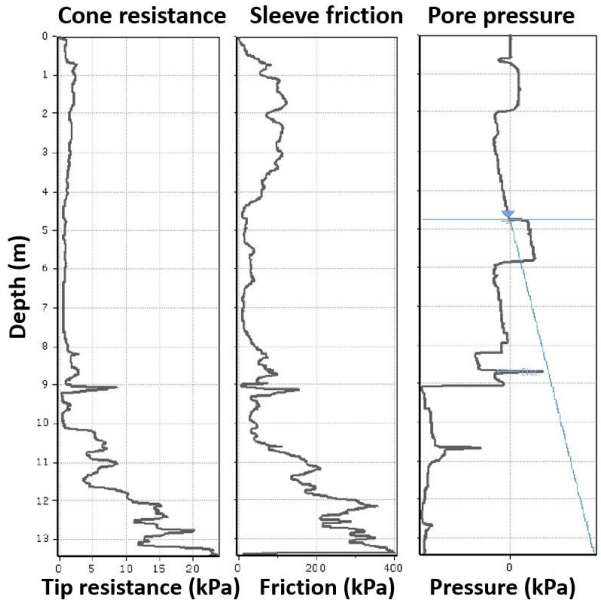

Figure 21. CPTU results from site 3 – Test number: CPTU-06

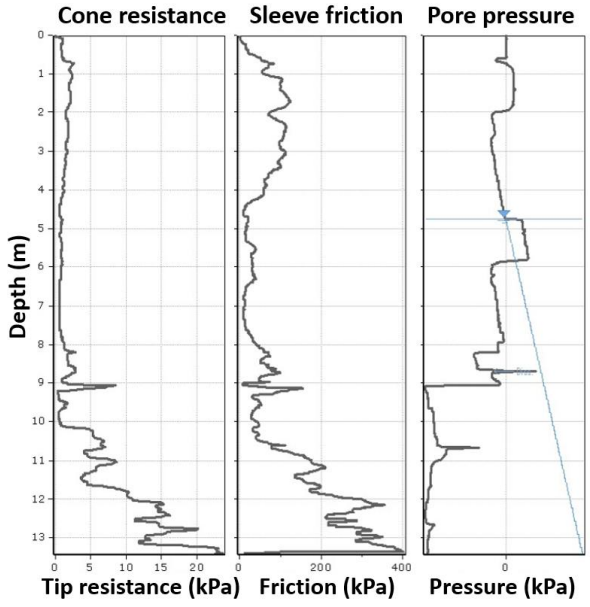

Figure 22. CPTU results from site 3 – Test number: CPTU-09

Table 5. TCT and CT tests results from site 3

Sample	S_u results from TCT tests (kPa)	σ_a results from CT tests (kPa)
SH-01	39,78	120,00
SH-02	11,53	50,00
SH-03	10,30	13,00
SH-04	42,99	200,00
SH-05	57,40	290,00

4.4. Site 4 – Cajamar

The site number four is located between the Bandeirantes highway and Anhanguera Highway, in the city of Cajamar, 30 km far from São Paulo city, also considered part of the metropolitan area of São Paulo.

In this site, CPTU and VT tests were executed, and undisturbed soil samples were collected with a Shelby tube sampler. Triaxial compression tests (TCT) and consolidations tests (CT) were executed with the samples.

The results of the tests are shown from the Figures 23 to 25 and Tables 6 to 7.

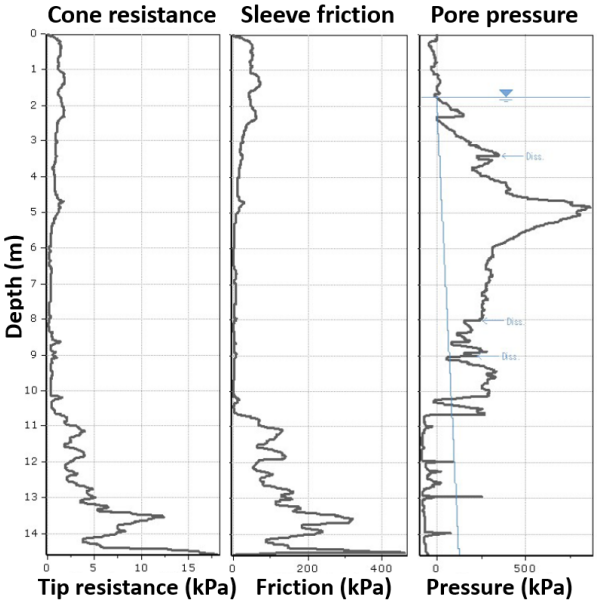

Figure 23. CPTU results from site 4 – Test number: CPTU-02

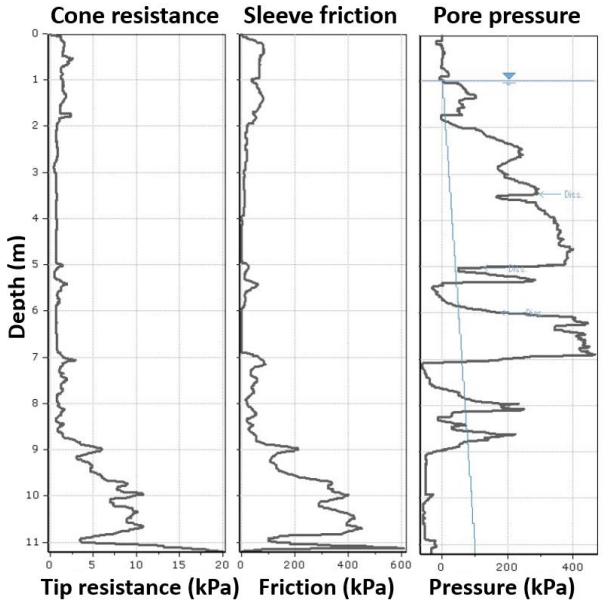

Figure 24. CPTU results from site 4 – Test number: CPTU-03

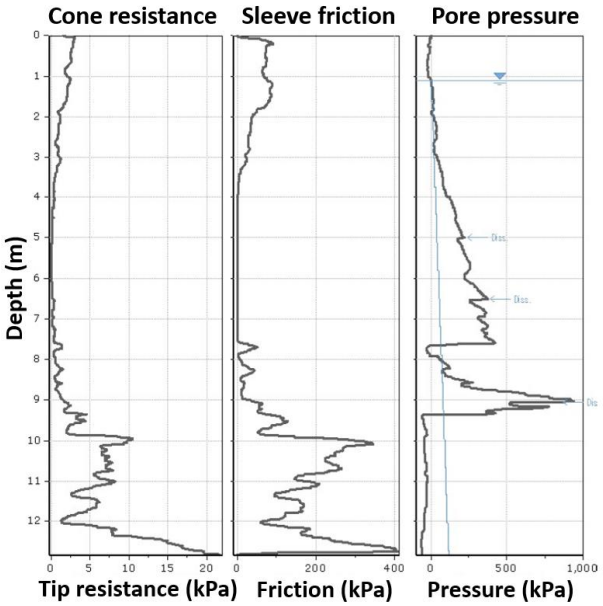

Figure 25. CPTU results from site 4 – Test number: CPTU-04

Table 6. VT test results from site 4

Test number	Depth (m)	Su peak (kPa)	Su remolded (kPa)
VT-201	6,00	11,18	0,90
VT-201	9,50	23,85	3,39
VT-202	4,50	27,56	8,25
VT-202	6,00	52,82	12,72
VT-203	7,00	24,15	2,54

Table 7. TCT and CT tests results from site 4

Sample	S_u results from TCT tests (kPa)	σ_a results from CT tests (kPa)
SH-201	30,15	130,00
SH-202	46,10	140,00
SH-203	18,55	110,00

4.5. Site 5 – Santos

The site number five is located in Santos, close to the Bagres' island, 50 km far from São Paulo city.

In this site, CPTU and VT tests were executed, and undisturbed soil samples were collected with a Shelby tube sampler. Only consolidations tests (CT) were executed with the samples.

The results of the tests are shown from the Figures 26 to 28 and Tables 8 to 9.

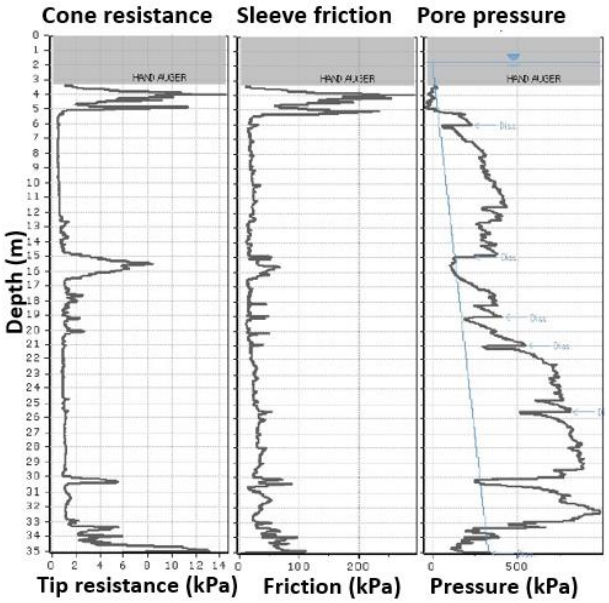

Figure 26. CPTU results from site 5 – Test number: CPTU-I01

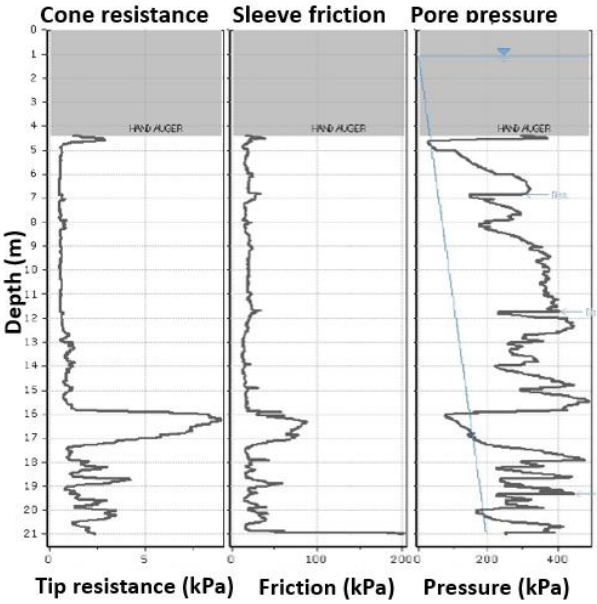

Figure 27. CPTU results from site 5 – Test number: CPTU-I02

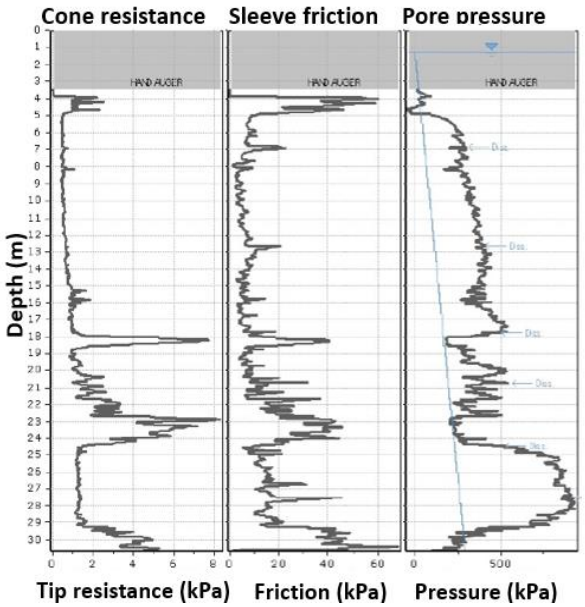

Figure 28. CPTU results from site 5 – Test number: CPTU-I03

Table 8. VT tests results from site 5

Test number	Depth (m)	Su peak (kPa)	Su remolded (kPa)
VT-I01	7,50	50,89	15,04
VT-I01	10,50	61,88	19,30
VT-I01	13,00	70,61	26,05
VT-I01	22,50	92,75	34,03
VT-I01	24,00	82,73	29,46
VT-I02	7,00	51,04	14,64
VT-I02	10,00	48,83	13,76
VT-I02	12,00	63,18	21,49
VT-I02	15,00	82,26	26,36
VT-I02	19,00	113,10	34,33
VT-I03	6,50	40,01	12,80
VT-I03	10,00	39,83	11,34
VT-I03	12,00	43,97	12,37
VT-I03	14,85	78,84	21,59
VT-I03	20,50	108,13	36,44

Table 9. CT tests results from site 5

Sample	Depth (m)	σ_a results from CT tests (kPa)
SH-I01	6,30	150,00
SH-I01	9,30	130,00
SH-I01	12,30	160,00
SH-I01	21,30	180,00
SH-I01	23,30	270,00
SH-I02	6,30	150,00
SH-I02	9,30	110,00
SH-I02	12,30	120,00
SH-I02	15,30	160,00
SH-I02	18,70	110,00
SH-I03	5,80	93,00
SH-I03	9,30	100,00
SH-I03	14,15	160,00
SH-I03	19,80	170,00
SH-I03	26,30	360,00

4.6. Site 6 – Osasco

The site number six is located close to the Mário Covas Highway in the city of Osasco, inside of the metropolitan area of São Paulo.

In this site, CPTU and VT tests were executed, and undisturbed soil samples were collected with a Shelby tube sampler. Triaxial compression tests (TCT) and consolidations tests (CT) were executed with the samples.

The results of the tests are shown from the Figures 29 to 31 and Tables 10 to 11.

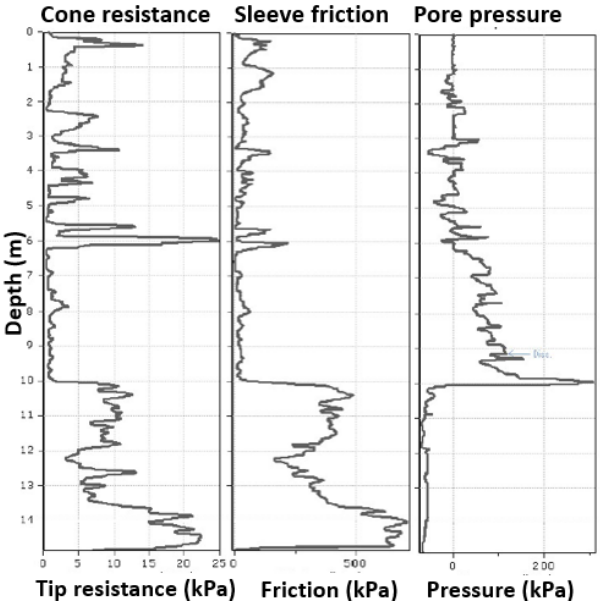

Figure 29. CPTU results from site 6 – Test number: CPTU-02

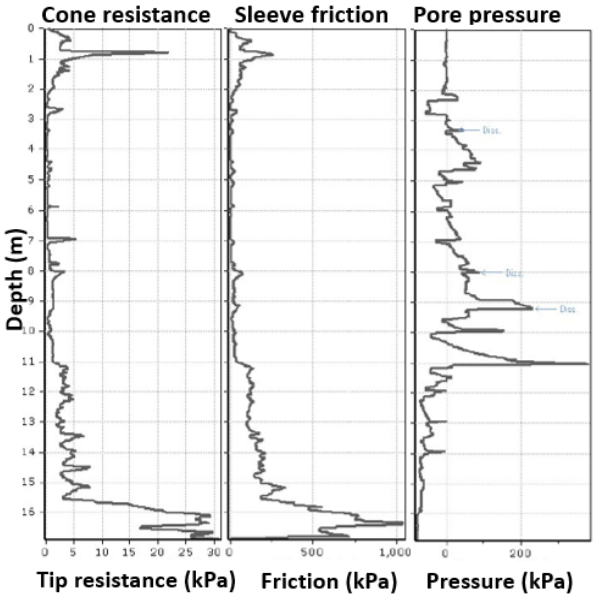

Figure 30. CPTU results from site 6 – Test number: CPTU-04

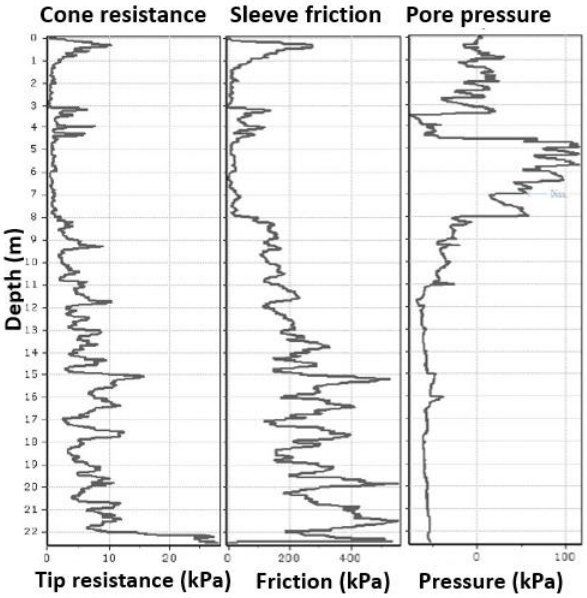

Figure 31. CPTU results from site 6 – Test number: CPTU-05

Table 10. VT test results from site 6

Test number	Depth (m)	Su peak (kPa)	Su remolded (kPa)
VT-01	7,00	31,00	10,28
VT-01	8,00	27,01	8,54
VT-01	9,00	42,58	16,47
VT-02	3,00	20,97	12,09
VT-02	5,50	38,47	7,06
VT-02	6,50	51,03	11,56
VT-03	4,00	85,57	18,45
VT-03	5,80	35,97	14,76
VT-03	6,50	54,18	13,35

Table 11. TCT and CT tests results from site 6

Sample	S_u results from TCT tests (kPa)	σ_a results from CT tests (kPa)
SH-01	37,82	88,00
SH-02	15,80	40,00
SH-03	60,74	65,00

4.7. Site 7 – Santos

The site number seven is located along the Anchieta highway, also in Santos.

In this site, CPTU tests were executed, and 1 undisturbed soil sample was collected with a Shelby tube sampler. Only a consolidation test (CT) was executed with the sample.

The results of the tests are shown from the Figure 32 and Table 12.

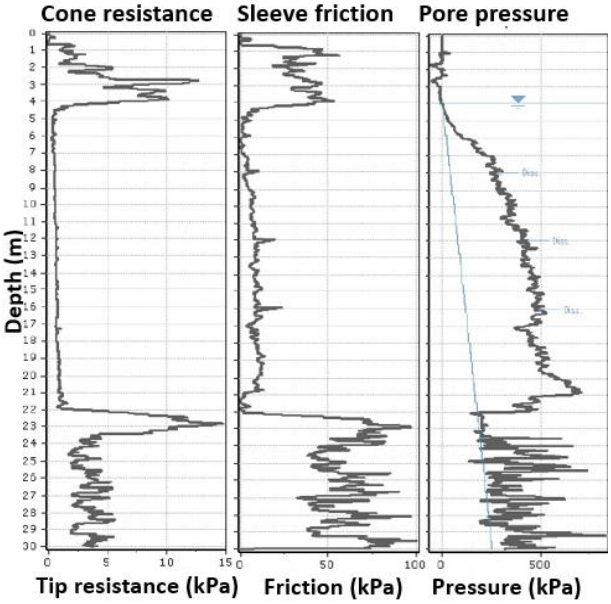

Figure 32. CPTU results from site 7 – Test number: CPTU-CN-03

Table 12. CT tests results from site 7

Sample	σ_a results from CT tests (kPa)
SH-CN-03	150,00

4.8. Site 8 – Santos

The site number eight is located close to the Barnabé island, also in Santos.

In this site, CPTU and VT tests were executed.

The results of the tests are shown from the Figure 33 and Table 13.

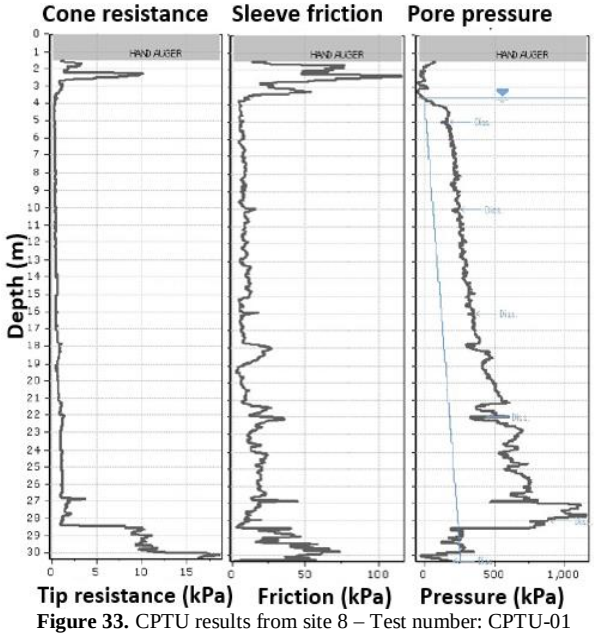

Figure 33. CPTU results from site 8 – Test number: CPTU-01

Table 13. VT test results from site 8

Test number	Depth (m)	Su peak (kPa)	Su remolded (kPa)
VT-201	3,00	38,85	4,81
VT-201	5,00	14,28	6,02
VT-201	7,00	24,22	8,02
VT-201	10,00	27,38	9,26
VT-201	13,00	23,65	7,76

Test number	Depth (m)	Su peak (kPa)	Su remolded (kPa)
VT-201	15,00	28,61	8,30
VT-201	19,00	28,10	9,25
VT-201	22,00	50,29	14,86
VT-201	25,00	12,82	NONE

5. Best correlations to estimate undrained shear strength (S_u) of soft and saturated clays of São Paulo region

Some correlations to estimate S_u of soft clays based on CPTU data are presented below. The estimated values were compared to laboratory tests results and to S_u directly estimated in VT, to demonstrate the accuracy of the results.

The σ'_v range was limited to the interval where the TCT and CT tests were executed and available.

5.1. CPTU data

Nine different equations used for estimating S_u were tested inputting piezocone penetration test data and two of them are presented in Sections 4.1.1 and 4.1.2 below.

5.1.1. Method 1

The equation that provides results most conservative and closer to S_u obtained from triaxial compression tests (TCT) is:

$$S_u = \frac{\Delta u}{N_{\Delta u}} \quad (1)$$

Where Δu = excess pore pressure during penetration ($\Delta u = u_2 - u_0$) and $N_{\Delta u}$ = bearing factor for excess pore pressures.

The recommended values of $N_{\Delta u}$ by [4], [2] and [5] were: 6, 5.88 and 6.5, respectively.

The S_u obtained from TCT executed in samples collected in different depths were compared to S_u estimated by Eq. (1), based on CPTU readings.

The factor that provided S_u values most conservative and closer to S_u obtained from TCT is $N_{\Delta u} = 6$, as suggested by [4]. The Eq. (1) adopting $N_{\Delta u} = 6$ will be called of Method 1 in this study.

The ratios of S_u obtained from Method 1 to S_u obtained from TCT for different ranges of acting effective stresses are shown in Figure 34 below.

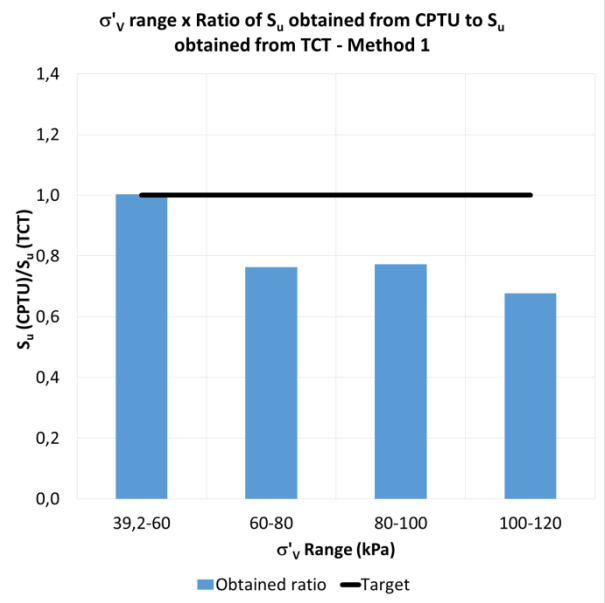

Figure 34. Ratio of S_u obtained from Method 1(CPTU data) to S_u obtained from TCT for ranges of effective stresses

The closer the ratio S_u (CPTU)/S_u (TCT) is to the unity, the better suited is the method used for S_u (CPTU) estimation. When the ratio is less than 1, the correlation provides values of S_u (CPTU) lower than S_u (TCT) and the estimated values are conservative, therefore, they are estimated in favor of safety.

Values of S_u estimated according to Method 1 (CPTU data) and obtained from TCT and vane tests (VT) were compared to each other. The referred comparison is presented in Figure 35.

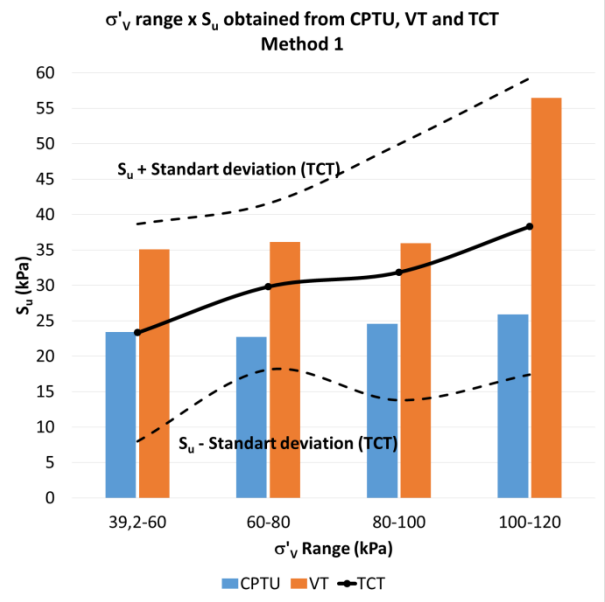

Figure 35. Comparison between S_u (TCT), S_u (VT) and S_u (CPTU) estimated according to Method 1

Values of S_u (CPTU) and S_u (VT) are within the range of values of S_u (TCT) considering the sample standard deviation, however, the values estimated by Method 1 (CPTU data) are lower than S_u (VT). Thus, Method 1, which uses CPTU data, provides S_u values more conservative than vane test does.

5.1.2. Method 2

The equation that provides results closer to S_u (TCT), but less conservative, is:

$$S_u = \frac{q_{net}}{N_{kt}} \quad (2)$$

Where q_{net} = net cone resistance ($q_{net} = q_t - \sigma_{v0}$) and N_{kt} = bearing factor for net tip resistance.

The recommended values of N_{kt} by [3], [2], [6] and [5] were: 12, 11.9, 14 and 11.8, respectively.

The factor that provided S_u values closer to S_u obtained from TCT is N_{kt} = 14, as suggested by [6]. The Eq. (2) adopting N_{kt} = 14 will be called of Method 2.

The ratios of S_u obtained from Method 2 to S_u obtained from TCT for different ranges of acting effective stresses are shown in Figure 36.

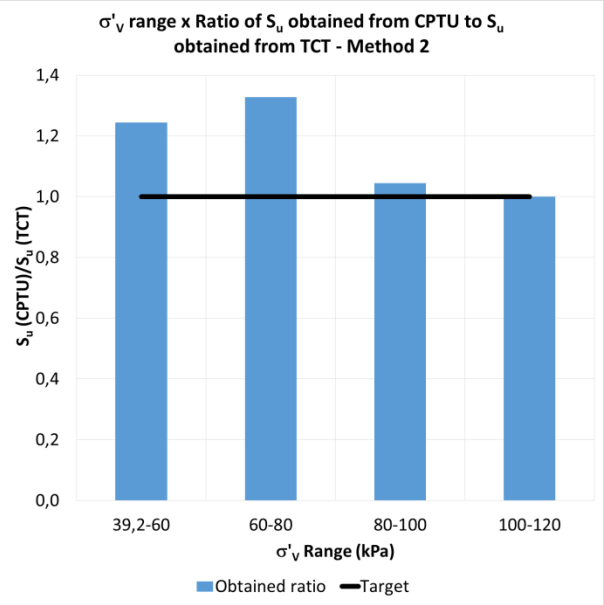

Figure 36. Ratio of S_u obtained from Method 2 (CPTU data) to S_u obtained from TCT for ranges of effective stresses

The ratios S_u (CPTU)/S_u (TCT) are close to the unity and for acting effective stresses between 39.2 and 100 kPa, the estimates ratios varies from 1.044 to 1.244.

Although the ratios observed are very close to 1, they are considered less conservative than those estimated according to Method 1.

Values of S_u estimated according to Method 2 (CPTU data) and obtained from TCT and vane tests (VT) were compared to each other, as presented in Figure 37.

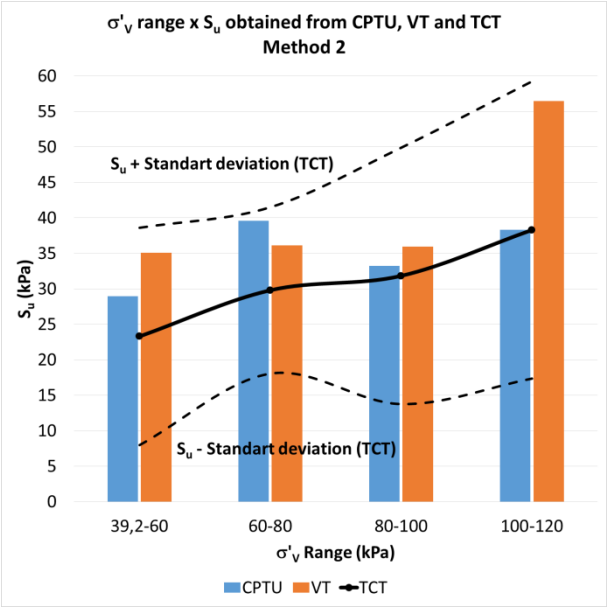

Figure 37. Comparison between S_u (TCT), S_u (VT) and S_u (CPTU) estimated according to Method 2

Just as noted in Figure 37, it is observed in Figure 4 that S_u (VT) are bigger than S_u (CPTU). Despite this, both of them are within the range of values of S_u (TCT) considering the sample standard deviation.

6. Best correlations to estimate pre-consolidation pressure (σ'_p) of soft and saturated clays of São Paulo region

Correlations to estimate pre-consolidation pressure of clays of São Paulo region based on CPTU and VT data are presented below. σ'_p calculated from in situ tests parameters were compared to σ'_p obtained from laboratory tests to emphasize the precision of the estimated results.

6.1. CPTU data

Four correlations from CPTU data to estimate pre-consolidation pressure values were tested and two of them are presented in Sections 5.1.1 and 5.1.2 below.

6.1.1. Method 3

The equation tested which provides σ'_p (CPTU) results closer to σ'_p obtained from consolidation tests (CT), is presented by [6] as follows:

$$\sigma'_p = OCR \; x \; \sigma'_v \quad (3)$$

$$OCR = Q_{tn} \; x \; k = \; Q_{tn} \; x \; 0.33 \quad (4)$$

Where OCR = overconsolidation ratio, σ'_v = effective stress, Q_{tn} = normalized cone resistance and k = 0.33, as recommended by [6].

σ'_p obtained from CT were compared to σ'_p estimated by Eq. (3) adopting k = 0.33, it will be called of Method 3.

The ratios of σ'_p obtained from Method 3 to σ'_p obtained from CT for ranges of effective stresses are presented in Figure 38.

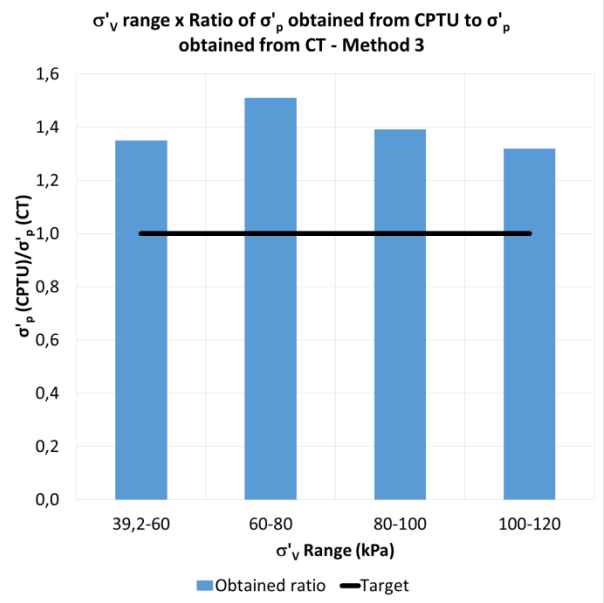

Figure 38. Ratio of σ'$_p$ obtained from Method 3 (CPTU data) to σ'$_p$ obtained from CT for ranges of effective stresses

The ratios σ'$_p$ (CPTU)/σ'$_p$ (CT) are greater than 1 and close to 1.5, which indicates that the values estimated according to Method 3 are almost 50% bigger than those directly obtained from CT.

Therefore, results obtained according to Method 3 could imply in consolidation settlements estimations considerably lower than the real ones.

Values of σ'$_p$ estimated according to Method 3 (CPTU data) were compared to those obtained from CT in Figure 39.

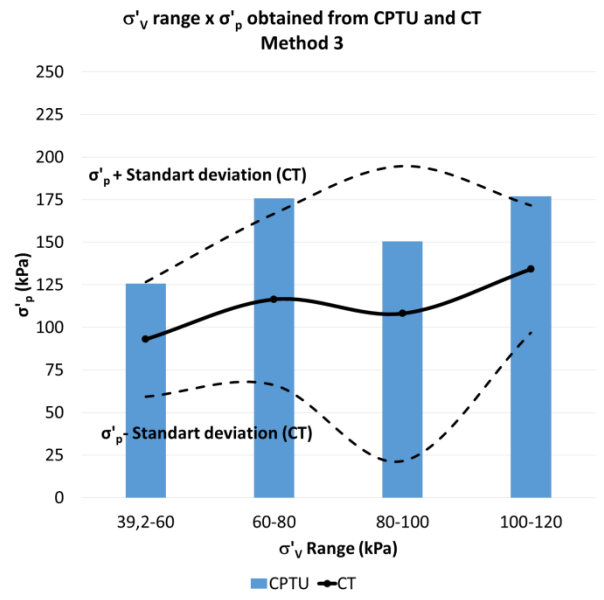

Figure 39. Comparison between σ'$_p$ (CT) and σ'$_p$ (CPTU) estimated according to Method 3

It is observed in Figure 39 that not all σ'$_p$ (CPTU) are within the range of values of σ'$_p$ (CT) considering the sample standard deviation.

In section 5.1.2 below, it is presented a suggestion of a new value of factor k.

6.1.2. Method 4

As the ratios σ'$_p$ (CPTU)/σ'$_p$ (CT), where σ'$_p$ (CPTU) were estimated according to Method 3, were close to 1.5. In this way, we propose to use k=0.22 that is the result of 0.33 divided by 1.5, to be applied in Eq. (4) associated to Eq. (3).

The Eq. (3) and Eq. (4) associated adopting k=0.22 will be called of Method 4 in this study.

The ratios of σ'$_p$ obtained from Method 4 to σ'$_p$ obtained from CT for different ranges of effective stresses are shown in Figure 40.

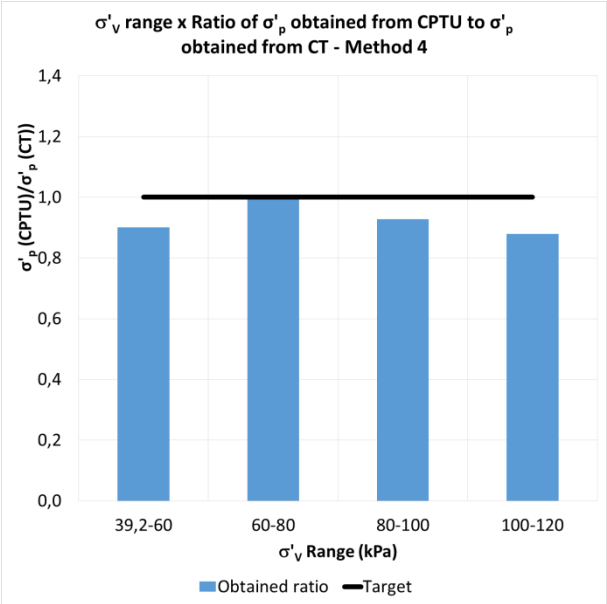

Figure 40. Ratio of σ'$_p$ obtained from Method 4 (CPTU data) to σ'$_p$ obtained from CT for ranges of effective stresses

The ratios σ'$_p$ (CPTU)/σ'$_p$ (CT) shown above are very close to the unity and as the values estimated are less than 1, Method 4 presents values of σ'$_p$ (CPTU) lower than σ'$_p$ (CT).

It implies in estimating consolidation settlements equal or slightly bigger than the real deformations. Therefore, Method 4 provides accurate pre-consolidation pressure values, which ones are more conservative than those estimated according to Method 3.

Values of σ'$_p$ estimated according to Method 4 (CPTU data) and obtained from CT were compared to each other in Figure 41.

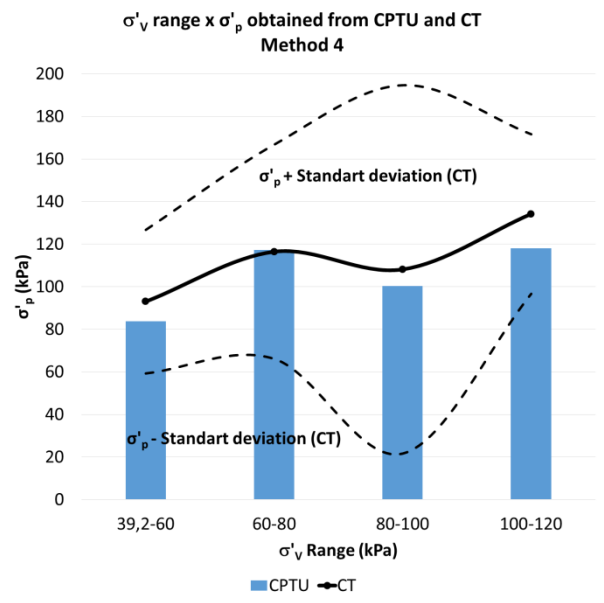

Figure 41. Comparison between σ'$_p$ (CT) and σ'$_p$ (CPTU) estimated according to Method 4

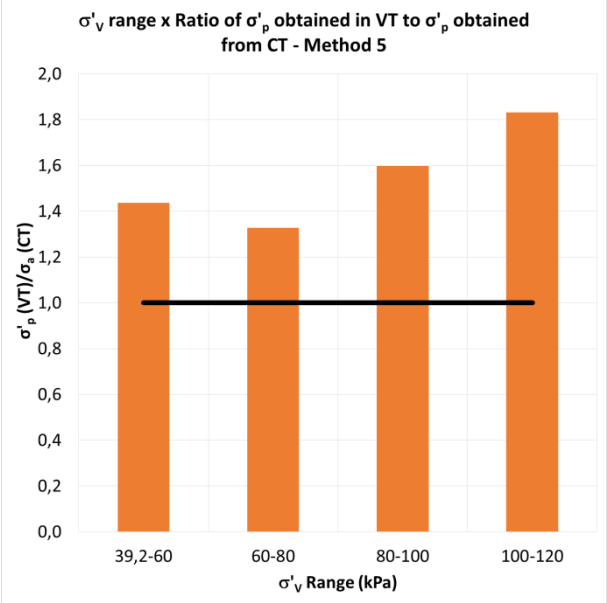

Figure 42. Ratio of σ'$_p$ obtained from Method 5 (VT data) to σ'$_p$ obtained from CT for ranges of effective stresses

In Figure 41, all σ'$_p$ (CPTU) estimated are close to σ'$_p$ (CT) and are within the range of values of σ'$_p$ (CT) considering the sample standard deviation.

6.2. VT data

Four equations inputting VT data were tested for estimating pre-consolidation pressure values and two of them are presented in Sections 5.2.1 and 5.2.2 below.

6.2.1. Method 5

The equation tested inputting VT data associated to Eq. (3) to determinate pre-consolidation pressure, which provides results closer to σ'$_p$ obtained from consolidation tests (CT), is:

$$OCR = 3.55\ x\ \left(\frac{S_u}{\sigma'_v}\right)^{0.66} \quad (5)$$

S_u in directly obtained from VST and σ'$_v$ is determined in CPTU.

The association between Eq. (3) and Eq. (5) will be called of Method 5 in this paper.

The ratios of σ'$_p$ obtained from Method 5 to σ'$_p$ obtained from CT for different ranges of effective stresses are presented in Figure 42.

The ratios σ'$_p$ (VT)/σ'$_p$ (CT) are greater than 1 and vary from 1.328 to 1.833 and indicate that the values estimated by Method 5 are at least 32.8% bigger than those directly obtained from CT.

Therefore, results obtained from VST correlation would imply in consolidation settlements estimations considerably lower than the real ones.

Values of σ'$_p$ estimated according to Method 5 (VT data) were compared to those obtained from CT in Figure 43.

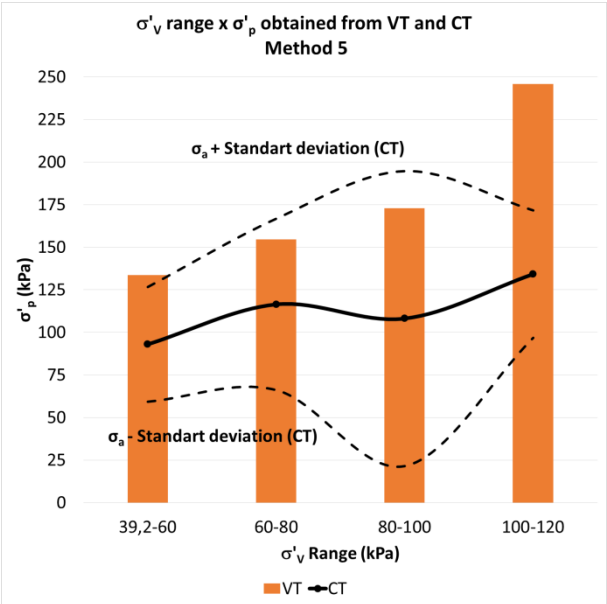

Figure 43. Comparison between σ'$_p$ (CT) and σ'$_p$ (VT) estimated according to Method 5

Not all σ'$_p$ obtained from VT are within the range of values of σ'$_p$ (CT) considering the sample standard deviation.

In section 5.2.2, it is presented a suggestion of a new equation for determining pre-consolidation pressure of clays using VT data.

6.2.2. Method 6

As the ratios σ'$_p$ (VT)/σ'$_p$ (CT) obtained from Method 5 vary from 1.328 to 1.833, we propose to divide OCR estimated according to Eq. (5) by 1.833. In this way, the following Eq. (6), to be associated to Eq. (3), is:

$$OCR = 1.937\ x\ \left(\frac{S_u}{\sigma'_v}\right)^{0.66} \quad (6)$$

The association between Eq. (3) and Eq. (6) will be called of Method 6 in this paper.

The ratios of σ'$_p$ obtained from Method 6 to σ'$_p$ obtained from CT for different ranges of effective stresses are presented in Figure 44.

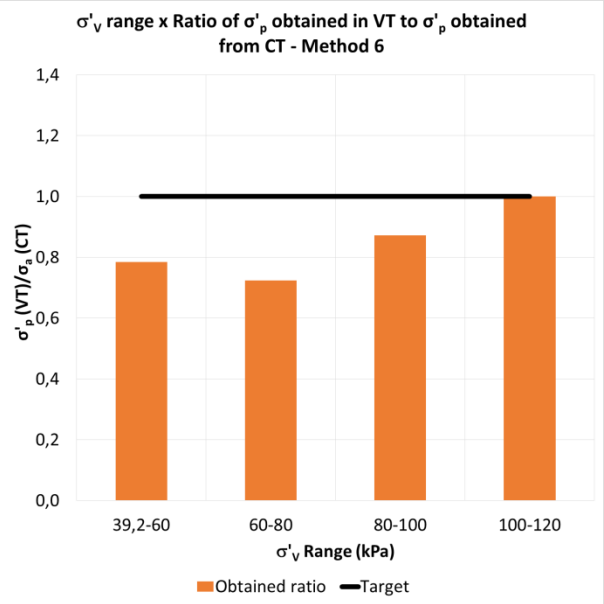

Figure 44. Ratio of σ'$_p$ obtained from Method 6 (VT data) to σ'$_p$ obtained from CT for ranges of effective stresses

The ratios σ'$_p$ (VT)/σ'$_p$ (CT) shown above are close to the unity and as the values estimated are less than 1, Method 6 can be considered more conservative to determinate pre-consolidation pressure values from VT data than Method 5.

Values of σ'$_p$ estimated according to Method 6 (VT data) and obtained from CT were compared to each other in Figure 45.

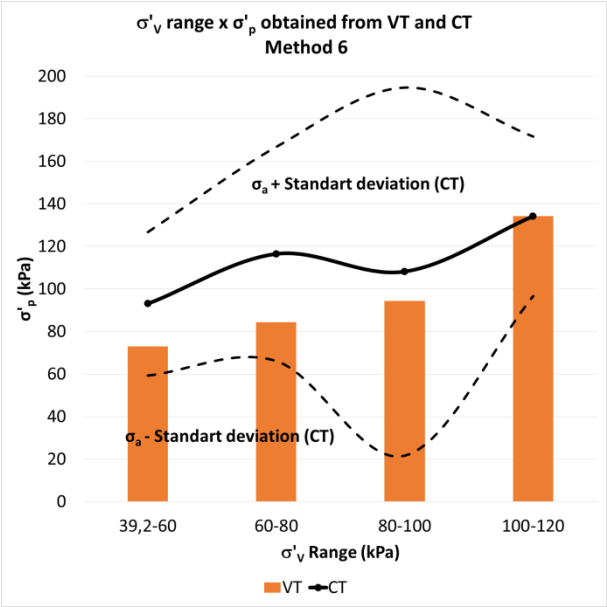

Figure 45. Comparison between σ'$_p$ (CT) and σ'$_p$ (VT) estimated according to Method 6

In Figure 45, all σ'$_p$ (VT) estimated according to Method 6 are within the range of values of σ'$_p$ (CT) considering the sample standard deviation.

In Figure 46 ratios σ'$_p$ (Method 4 - CPTU)/σ'$_p$ (CT) and σ'$_p$ (Method 6 - VT)/σ'$_p$ (CT) were compared to each other.

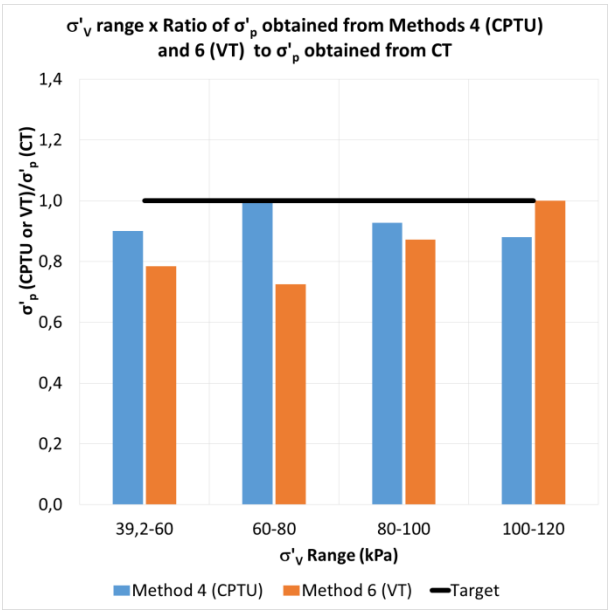

Figure 46. Comparison σ'$_p$ (Method 4 - CPTU)/σ'$_p$ (CT) and σ'$_p$ (Method 6 - VT)/σ'$_p$ (CT)

The pre-consolidation pressures estimations according to Method 4, based on CPTU data, are more accurate for acting effective stresses until 100 kPa.

While for effective stresses range from 100 to 120 kPa, the results estimated according to Method 6, based on VT readings, are more precise than those based on CPTU data are.

7. Conclusions

The estimative of undrained shear strength and pre-consolidation pressure from CPTU and VT data are rep-

resentative and can provide accurate values of parameters of soft clays of São Paulo region to be considered in foundation, soil reinforcement and soil consolidation designs.

Assuming the laboratory tests results as reference, the analysis of CPTU readings through Method 1 and Method 4 provided the best results of S_u and σ'_p , respectively, considering precision and safety simultaneously. By the same optic, the analyses of the VT data through Method 6 provided the best pre-consolidation pressure estimation.

References

[1] Almeida, M.S.S., Marques, M.E.S. "Aterros sobre Solos Moles: Projeto e Desempenho" (Embankments on Soft Soils: Design and Performance), 1st edition, Oficina de Textos, São Paulo, Brazil, 2011. (in Portuguese)

[2] Low, H. E., Lunne, T., Andersen, K.H., Sjursen, M. A., Li, X., Randolph, M.F., "Estimation of intact and remoulded undrained shear strengths from penetration tests in soft clays, Geotechnique 60 (11), pp. 843 – 859, 2010

[3] Lunne, T., Randolph, M.F., Chung, S.F., Andersen, K.H., Sjursen, M. "Comparison of cone and T-bar fac-tors in two onshore and one offshore clay sediments". In: Proceedings of the International Symposium on Frontiers in Offshore Geotechnics, Perth, Australia, 2005, pp. 981-989

[4] Lunne, T. "The CPT in offshore soil investigations - a historic perspective". In: 2nd International Symposium on Cone Penetration Testing, Los Angeles, United States of America, 2010

[5] Mayne, P.W. "Evaluating effective stress parameters and undrained shear strengths of soft-firm clays from CPT and DMT". InGeotechnical and Geophysical Site Characterization 5, Sydney, Australia, 2016, pp. 19-39

[6] Robertson P.K., Cabal K.L. "Guide to Cone Penetra-tion Testing 6th edition". Gregg drilling & Testing, Inc. Signal Hill, United States of America, 2015

[7] Schnaid, F. "In Situ Testing in Geomechanics, the Main Tests", 1st edition, Taylor and Francis, New York, United States of America, 2009

[8] Schnaid, F, Odebrecht, E.. "In Situ Tests and theirs applications to Foundations Engineering 2th edition", Ensaios de Campo e suas Aplicações à Engenharia de Fundações 2ª edição, 2th edition, Oficina de Textos, São Paulo, Brazil, 2012. (in Portuguese)