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The Site Characterization of Central Jakarta Soft Soil Using CPTu and Laboratory Test

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ABSTRACT Construction activities has been named as one of the contributing factors to Jakarta's alarming rate of land subsidence, which ranges between 1 to 15 cm annually, and up to 28 cm in some locations. This problem is commonly known as settlement, and the affected soft soil is usually attributed to under-consolidating soil (UC). In regards to that matter, this study aims to characterize the soft soil layer in Central Jakarta using the Cone Penetration Test with pore pressure measurement (CPTu) and laboratory assessment. In addition, Undrained Shear Strength (S_u) and Pore Pressure Ratio (B_q and B_q^*) methods were used to estimate the over-consolidation Ratio (OCR) values. The data collected from 94 boreholes and 30 CPTu showed the soft soil layers in Central Jakarta, which was dominated by high-plasticity silty clay (CH) and clayey silt (MH). The layers are detected between the depth of 0 – 25 m and are characterized by high natural moisture content, void ratio, liquidity index, and compression index values. Within this layer of under consolidated soils, the indication of relatively low dry unit weight was also present. Furthermore, the laboratory tests showed several correlations related to under-consolidating soil, i.e. void ratio to in-situ effective stress, void ratio to compression index, and compression index to natural moisture content. The CPTu test interpretations returned a number of under-consolidation soil layer samples in Central Jakarta. Moreover, the result also indicates the presence of under-consolidating properties, as well as normally consolidated and lightly over-consolidated.

KEYWORDS Soft soil; Degree of consolidation; OCR; CPTu; Under-consolidating soil

1 INTRODUCTION

Jakarta City has experienced significant and rapid economic growth. The process requires appropriate infra-structural improvement to ensure sustainability. Meanwhile, the project development cycle is often faced with several field-based problems, including the land subsidence phenomenon.

Jakarta Bay is located on a 200 to 300 m thick quaternary deposit soil layer (Rismianto & Mak, 1993) which is above the tertiary deposit layer. The location is dividable into three main structures, including the oceanic and non-oceanic Pleistocene deposits, Pleistocene volcanic deposits, as well as the oceanic deposits and Holocene floodplains. Figure 1 shows further illustrations of this formation in the Hydro-Geology Cross Section of Jakarta City.

According to Abidin (Abidin et al., 2001; Abidin et al., 2014), the land subsidence rate in Jakarta ranges from 1 to 15 cm/year, although 20 to 28 cm/year was recorded in some locations. Additionally, four causative factors have been identified. These include groundwater pumping, construction loads, natural consolidation processes in the alluvium soil layer, and tectonic activity (Rismianto & Mak, 1993; Murdohardono & Sudarsono, 1998).

Land subsidence resulting from construction loads is often referred to as settlement. These formations are reportedly caused by the compounding clay layer, and develop from the increased compressive stress caused by construction activities and/or other weights. Moreover, additional compressive stress increases after the introduction of pore water, which dissipates over time and causes changes to the soil volume.

The consolidation process observed in soft clay soils is attributed to natural processes based on loadings formed through geological formations, including sedimentation (Olsen & Schuster, 1984). However, under-consolidating soil (UC) are known to yield problems in construction, consisting of large settlements, negative skin friction on pile foundations, excess pore water pressure due to pile driving, and excavation stability.

The stress history in under-consolidating soil is an important parameter in engineering designs (Liu, et al., 2014). This is due to certain intrinsic characteristics compared to normally consolidated (NC) and over-consolidated (OC) soil samples. Furthermore, this research discusses the properties of soft soils consolidating in the Central Jakarta area. This involved using in-situ test data, including CPTu and laboratory assessment figures, encompassing index properties and an oedometer was used to evaluate consolidation.

1.1 Soil Classification

Several experts have proposed the classification of soil type using the CPTu test. Robertson (Lunne et al., 1997) reportedly created two charts using this method. The first was based on the corrected cone tip resistance value (q_t) with a friction ratio value (F_R) which expresses the ratio between the sleeve (f_s) and tip resistance (q_c). Furthermore, the second chart was established. on the value of q_t and pore pressure ratio (B_q) as indicated in Figure 2. Table 1 shows the unit weight of each soil type.

The pore pressure ratio (Lunne et al., 1997) is determined using the parameters measured from the CPTu test and using equation 1:

$$B_q = \frac{\Delta u}{q_t - \sigma'_v} \qquad (1)$$

Where
Δu = excess pore pressure
q_t = cone resistance corrected = $q_c + u_2(1-a)$
σ'_v = effective stress

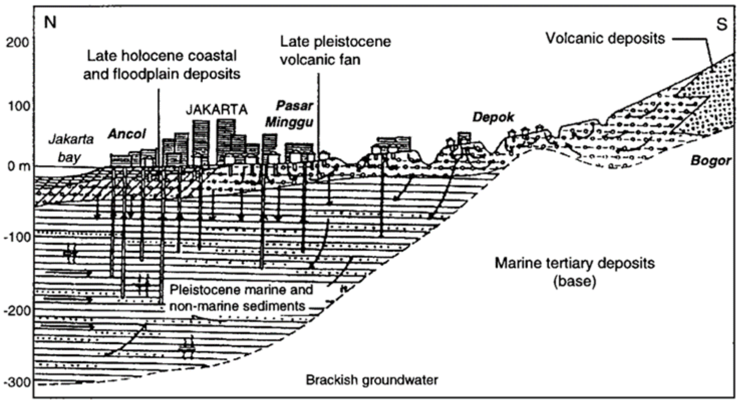


Figure 1. Hydro-Geology Cross Section of Jakarta (Rismianto & Mak, 1993)

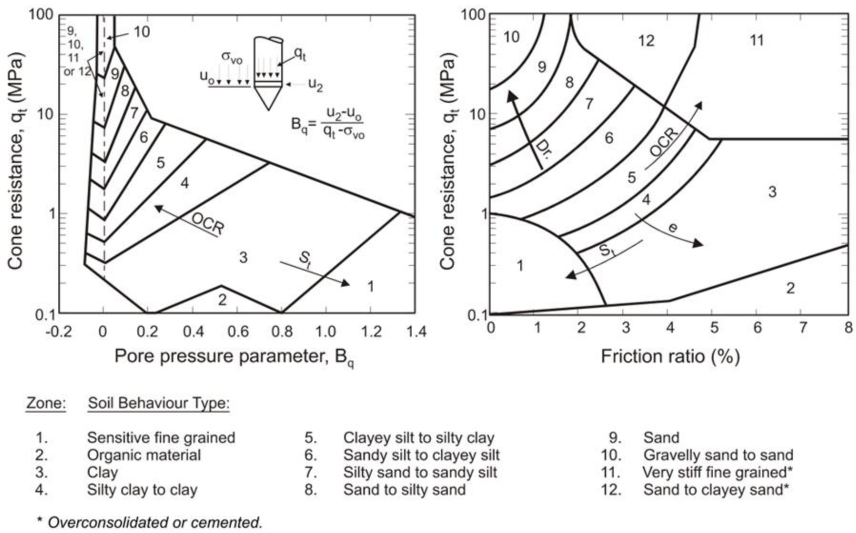


Figure 2. Soil behavior type classification system from CPTu (Lunne et al., 1997)

Table 1. Approximate Unit Weight (Lunne et al., 1997)

Zone	Approximate Unit Weight (kN/m³)
1	17.5
2	12.5
3	17.5
4	18
5	18
6	18
7	18.5
8	19
9	19.5
10	20
11	20.5
12	19

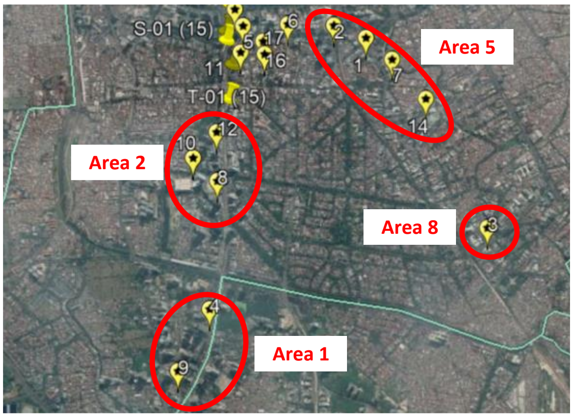
1.2 Soil Condition and Profile

The soil in the research area was investigated through drilling, SPT, and CPTu tests. Figure 3 shows the investigation was conducted on 16 projects in the Central Jakarta area, using a total of 94 drilling and 30 CPTu points. The individual projects were grouped into 8 main areas based on location and similarity of the interpreted soil profile as indicated in Figure 4. Moreover, Table 2 presents the soil profiles were interpreted based on drilling data, SPT test, and CPTu test.

1.3 Soil Properties

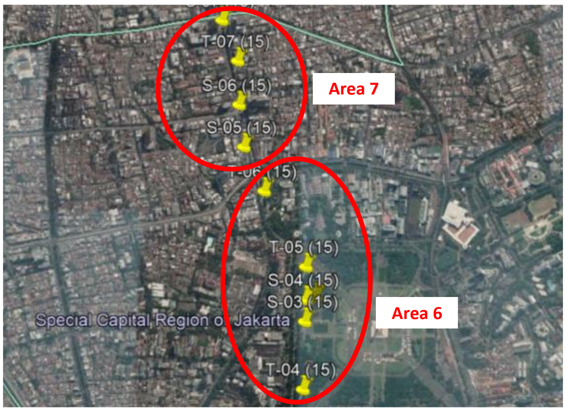
The laboratory test results were used to determine the soil's physical and mechanical properties. However, secondary data were also used in this research.

Figure 3. Map of CPTu testing and drilling locations in Central Jakarta



a. Locations of Project Area 1, 2, 5, and 8

b. Locations of Area 3, 4, and 5



c. Locations of Areas 6, and 7

Figure 4. Map of Soil Investigation Project Area

1.4 Physical Properties

The physical properties evaluated include moisture content, void ratio, dry and wet bulk density, liquid limit, plastic limit, plasticity index, and liquidity index. Figure 5 illustrates the distribution of the plastic limit (PL) and liquid limit (LL) at various depths. The PL values recorded at 0 to 25 m range from 25 to 120% while 25 to 50% were located in areas farther than 25 m. Meanwhile, the LL observed at 0 to 25 m ranged from 50 to 200%, while those greater than 25 m were 30 to 100%.

Table 2. Soil profile in each area

Area	Depth (m)	Soil Type	Consistency / Density
Area 1	0 - 14	CLAY	Very Soft to Medium
	14 - 20	CLAY	Stiff to Hard
	20 - 26	SAND	Dense
	26 - 44	CLAY	Very Stiff to Hard
	44 - 54	SAND	Dense to Very Dense
	54 - 80	CLAY	Very Stiff to Hard
Area 2	0 - 5	CLAY	Very Soft to Medium
	5 - 8	CLAY	Stiff
	8 - 17	SAND	Dense to Very Dense
	17 - 22	CLAY	Very Stiff to Hard
	22 - 28	SAND	Dense to Very Dense
	28 - 38	CLAY	Very Stiff to Hard
	38 - 44	SAND	Dense to Very Dense
	44 - 84	CLAY	Very Stiff to Hard with some sand lenses
	84 - 88	SAND	Dense to Very Dense
	88 - 104	CLAY	Hard
	104 - 110	SAND	Dense to Very Dense
	110 - 120	CLAY	Hard
Area 3	0 - 2	CLAY	Stiff
	2 - 22	CLAY	Very Soft to Medium
	22 - 27	CLAY	Stiff
	27 - 41	SAND	Loose to Very Dense
	41 - 100	CLAY	Stiff to Hard
Area 4	0 - 8	CLAY	Very Soft to Medium
	8 - 18	SAND	Very Loose to Medium
	18 - 25	CLAY	Soft to Stiff
	25 - 39	SAND	Medium to Very Dense
	39 - 60	CLAY	Very Stiff to Hard
Area 5	0 - 15	CLAY	Soft to Medium
	15 - 19	CLAY	Medium to Very Stiff
	19 - 22	SAND	Very Dense
	22 - 29	CLAY	Medium to Hard
	29 - 36	SAND	Very Dense
	36 - 60	CLAY	Very Stiff to Hard
Area 6	0 - 8	CLAY	Very Soft to Medium
	8 - 12	CLAY	Medium to Stiff
	12 - 40	CLAY	Stiff to Hard
Area 7	0 - 3	SAND	Medium Dense
	3 - 8	CLAY	Soft to Medium
	8 - 15	CLAY	Medium to Hard
	15 - 23	SAND	Dense to Very Dense
	23 - 31	CLAY	Medium to Very Stiff
	31 - 50	CLAY	Very Stiff to Hard
Area 8	0 - 10	CLAY	Medium to Very Stiff
	10 - 35	CLAY	Very Stiff to Hard
	35 - 44	SAND	Dense to Very Dense

44	-	50	CLAY	Hard

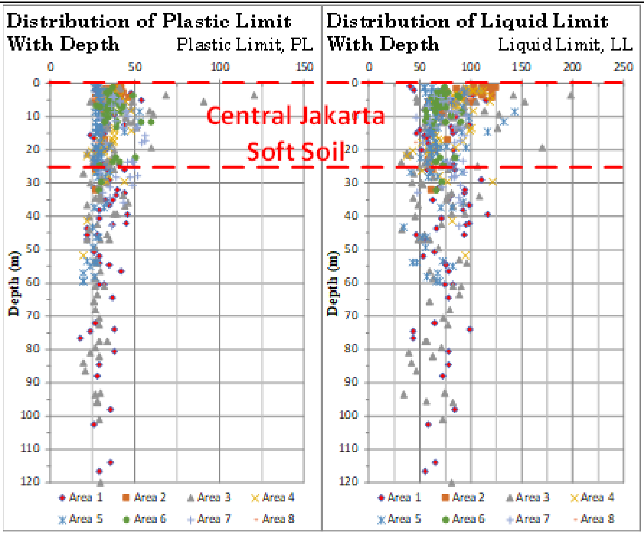


Figure 5. Distribution of PL and LL with Depth

The PI and LI values were further calculated from LL, PL, and moisture content. Figure 6 presents the distribution in relation to depth, and the soil obtained between 0 and 25 m demonstrated PI values in the range of 20 to 110 and LI of 0 to 3, while areas deeper than 25 m show LI values between 0 to 1. In addition, values > 1 are an indication of soil being in a liquid state and exhibiting a soft consistency.

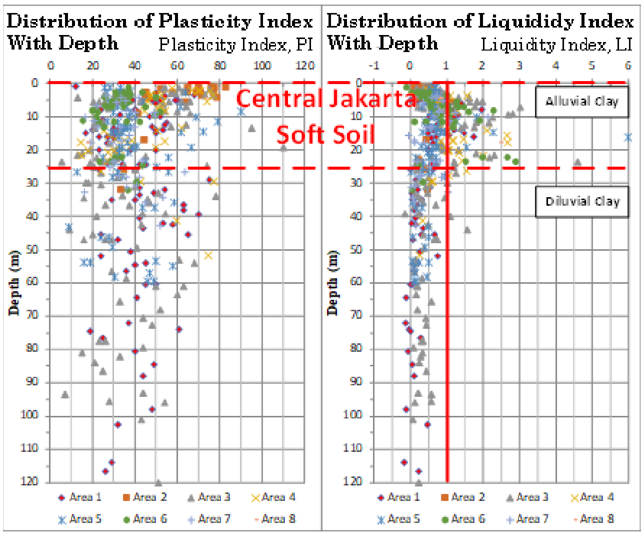


Figure 6. Distribution of PI and LI with Depth

Figure 7 depicts the LL and PI values used to plot a Casagrande's Plasticity Chart, and consequently determine the soil classification. The results indicate the soil in Central Jakarta to be dominated by clay and silt with high plasticity (CH and MH).

Figure 8 shows the moisture content distribution, where the soil layers at 0 to 25 m demonstrated values between 40 and 250%. Meanwhile, areas deeper than 25 m ranged between 25 and 50%. In addition, higher values are indicators of soft soil.

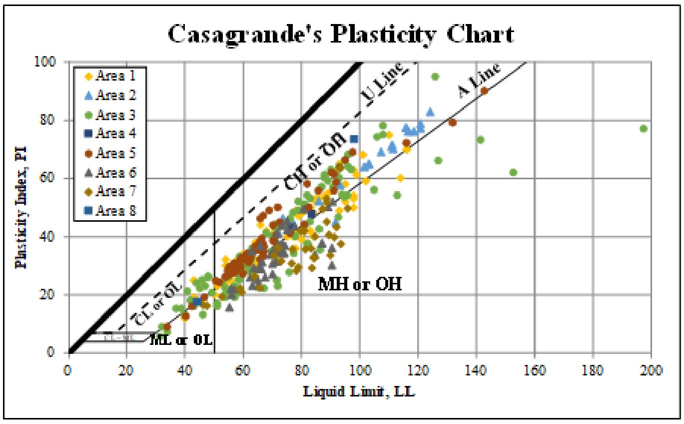


Figure 7. Data Distribution on Casagrande's Plasticity Chart

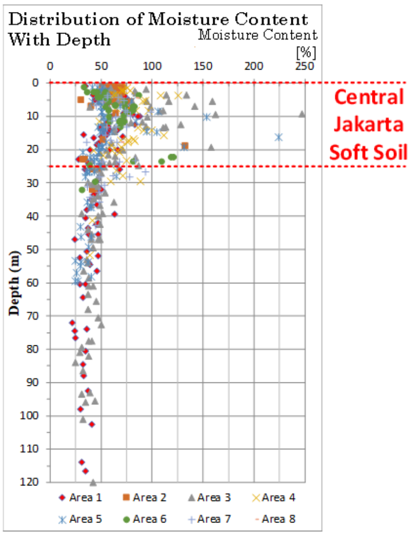


Figure 8. Distribution of Moisture Content with Depth

Figure 9 exposes a relatively high void ratio (from 2 to 6) in the soil layer at depth of 0-25 m, while those deeper than 25 m were approximately 1. Therefore, high values are noteworthy indicators of alluvium soil, while diluvium soils are present in levels with relatively low markers.

The dry unit soil weight obtained at a depth of 0 to 25 m was discovered in the range of 6 to 16 kN/m^3 while those at deeper levels had 11 to 16 kN/m^3 as shown in Figure 10. In addition, the dry unit tends to weigh lesser than 10 kN/m^3, indicating the soil layer was recently deposited and is characterized by a tendency to consolidate.

1.5 Mechanical Properties

The mechanical properties of the soil tested in the laboratory include the compression index (C_c) which was measured using an oedometer. Figure 11 shows the value recorded for samples collected at a depth of 0 to 25 m to be in the range of 0.4 and 2.6, while < 1 was reported at deeper levels. Furthermore, $C_c > 0.4$ is an indication of high and easy compressibility property of the soil sample, featuring a generally soft consistency. This outcome is consistent with the results of previous studies on soil physical properties, where a soft consistency was determined in samples collected at a depth of 0 to 25 m in the Central Jakarta area.

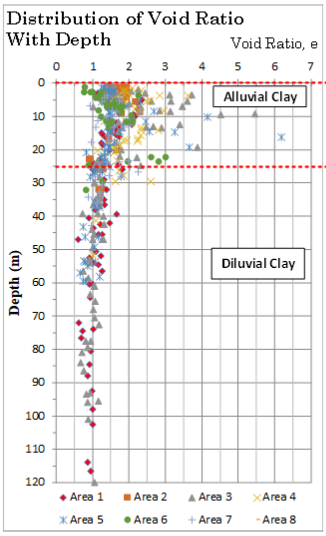


Figure 9. Distribution of Void Ratio with Depth

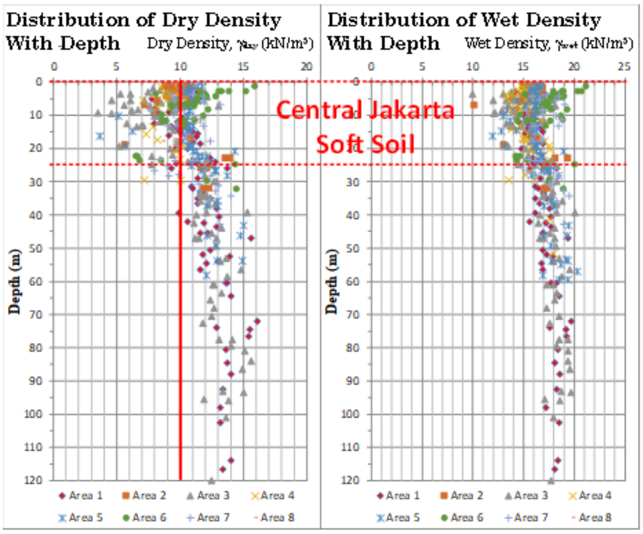


Figure 10. Distribution of Soil Unit Weight with Depth

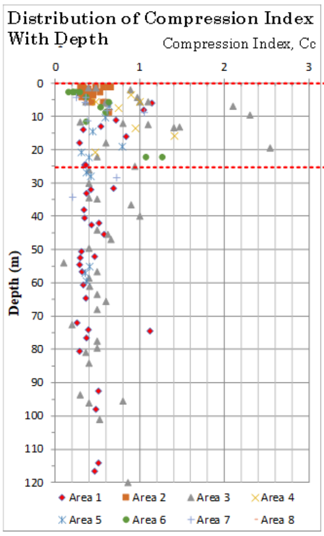


Figure 11. Distribution of C_c with Depth

1.6 Correlation of Geotechnical Parameters

The physical and mechanical properties of the soil were correlated and Figure 12 showed the association between the void ratio (e) and the effective stress of the soil sample (σ_v'). The graph generated was used to formulate the following equation:

$$e = 8.8 \times {\sigma_v'}^{-0.357} \tag{2}$$

The soil sample with effective stress < 400 kPa was observed to have a void ratio value > 1. This is an indication of soft consistency and high compressibility.

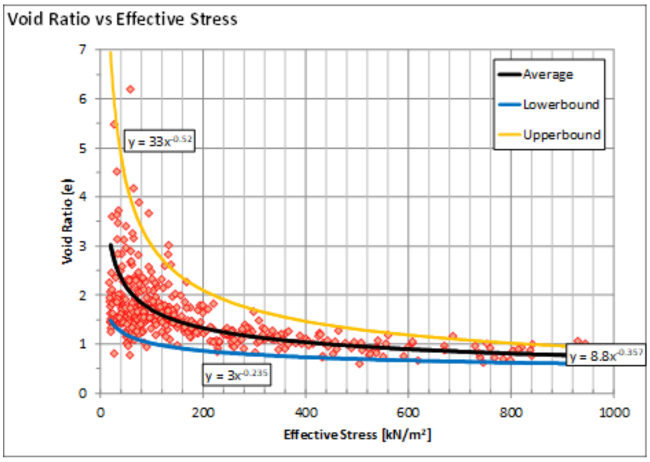


Figure 12. Correlation between Void Ratio with Effective Stress

Figure 13 shows a highly significant correlation between larger void ratios and greater soil compression index. This relationship is represented using the following Equation.

$$C_c = 0.4587 \times e \tag{3}$$

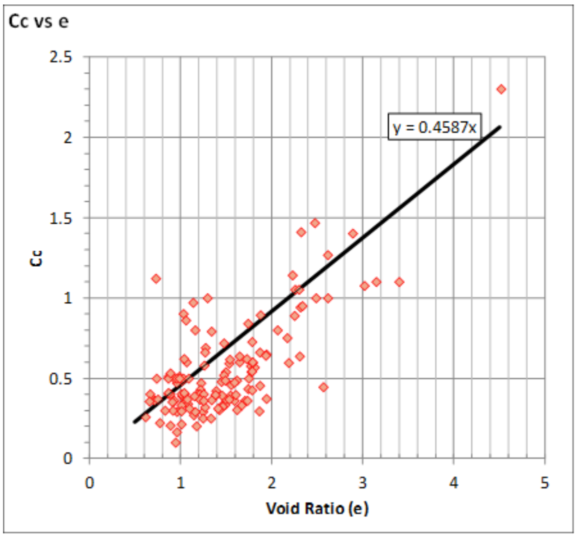


Figure 13. Correlation between C_c with Void Ratio

Figure 14 shows the correlation between the compressibility index and the natural soil moisture content (w_n). The equation for the relationship is:

$$C_c = 0.0108 \times w_n \tag{4}$$

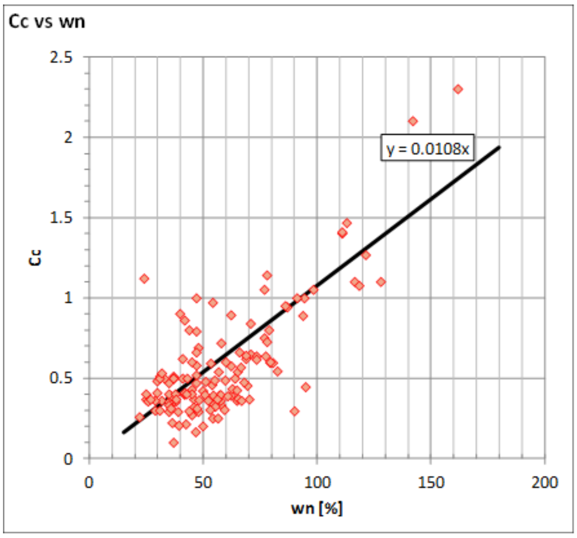


Figure 14. Correlation between C_c with Moisture Content

1.7 Undrained Shear Strength

The undrained shear strength (S_u) was determined using the CPTu results based on the cone tip resistance value (q_c) as indicated in Equation 5:

$$S_u = \frac{(q_t - \sigma_{vo})}{N_{kt}} \tag{5}$$

Mayne and Peuchen (Mayne & Peuchen, 2018) established a relationship between the N_{kt} coefficient and pore pressure ratio (B_q). This was based on 62 types of clay soil as shown in Figure 15, and the correlation was indicated in the following equation:

$$N_{kt} = 10.5 - 4.6 \times \ln(B_q + 0.1) \tag{6}$$

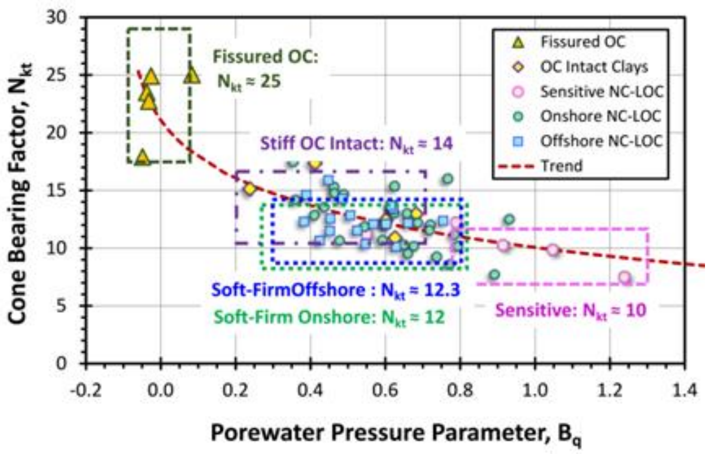


Figure 15. Correlation between N_{kt} with B_q(Mayne & Peuchen, 2018)

Begemann was the first to show the potential to measure the undrained shear strength of clay soil (S_u) using thr CPT cone sleeve resistance (f_s). Furthermore, subsequent studies supported this claim and a correlation was established between the S_u value from the triaxial UU test and the f_s value measured in the CPT test (Anagnostopoulos et al., 2003). Figure 16 show the recommended $f_s/_{S_u}$ ratio for the electrical cone to be 1.00.

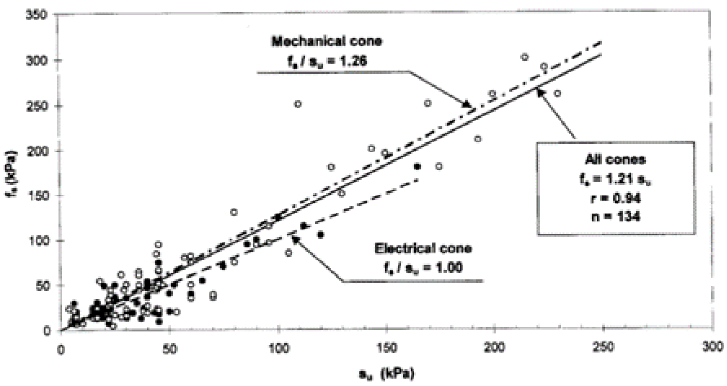


Figure 16. Correlation between S_u with f_s (Anagnostopoulos et al., 2003)

1.8 OCR and Degree of Consolidation

The undrained shear strength (S_u) values of soil were obtained by correlating q_t, N_{kt}, and f_s while the OCR and degree of consolidation were derived through the B_q, B_q^*, and S_u methods. Consequently, the results obtained were applied as a parameter to determine the stress history of the soil layer. According to Mesri *et al.* (1989), the correlation between S_u and σ_v' in normally consolidated (NC) soils was:

$$S_u = 0.22 \times \sigma_v' \tag{7}$$

S_u/σ_v' values less than 0.22 indicate the presence of an under-consolidating soil (UC). Meanwhile, the OCR obtained using S_u method was calculated as follows:

$$OCR = \frac{S_{u\,from\ CPTu}}{S_{u\,NC\ Clay}} \tag{8}$$

2 B_q and B_q^* METHODS

The degree of soil layer consolidation in an area was calculated by interpreting the CPTu results and the correlation between the pore pressure ratio (B_q) and OCR (Anagnostopoulos et al., 2003). In addition, the B_q value was calculated using the relationship shown previously in eq.1.

Figure 17 displays the graph presented by Rahardjo (Rahardjo, 2016) to correlate B_q and OCR. The results show values < 1 represent the degree of consolidation (in decimal) for under-consolidating soil. Moreover, the curves discovered on the graph were presented using the following Equation 9:

$$OCR = \frac{1}{1.2\,B_q + 0.1} \tag{9}$$

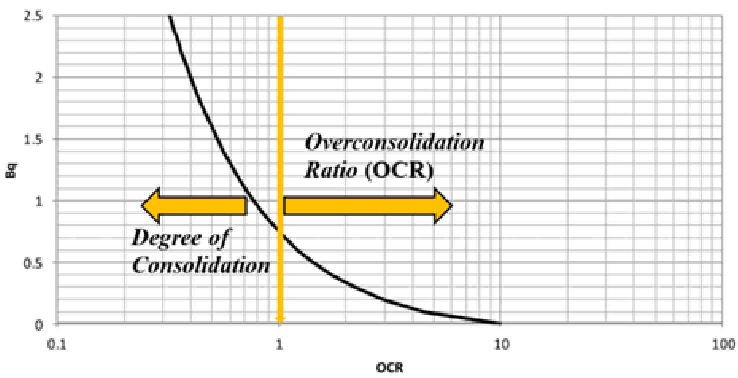


Figure 17. Correlation between OCR and B_q (Rahardjo, 2016)

Setiawan and Rahardjo (Ricky, 2017) proposed a modified parameter for pore pressure ratio (B_q^*), which is independent of the effective soil stress (σ_v'). This parameter was calculated as follows:

$$B_q^* = \frac{u_2}{q_T} \tag{10}$$

Where:
u_2 = measured total water pressure, and
q_T = the corrected conus tip pressure.

Figure 18 exhibits the use of this equation to correlate OCR value and B_q^*.

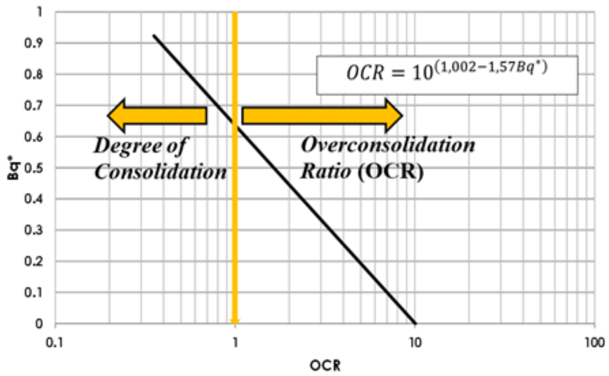


Figure 18. Correlation between OCR and B_q^* (Ricky, 2017)

3 RESULTS OF THE CPTU TESTS

Twenty (20) high-quality data sets were selected to demonstrate the interpretation method. The CPTu test was performed to obtain the corrected tip resistance (q_t) and pore pressure values (u_0 and u_2). Subsequently, the undrained shear strength values, B_q and B_q^* were calculated to determine the OCR of the soil layer.

The clay was characterized by stiff to hard consistency and the sand layers were not interpreted. However, the groundwater level was determined by extrapolating the water pressure on the sand layer. Figures 19 to 23 show the CPTu test result and the possible interpretations.

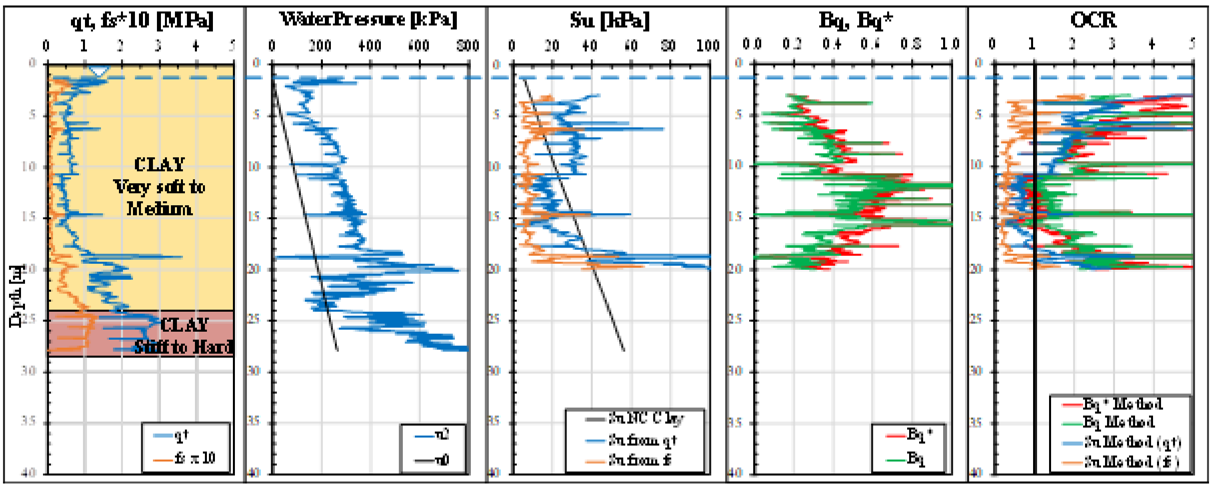


Figure 19. Result of CPTu-2 at Project 15B represents Area 3

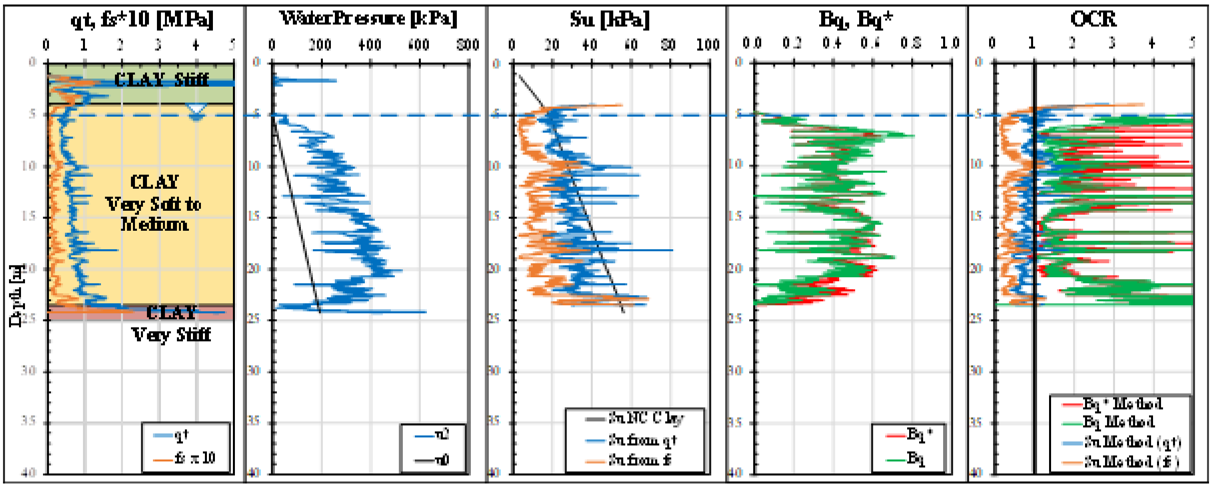


Figure 20. Result of CPTu-1 at Project 17 represents Area 3

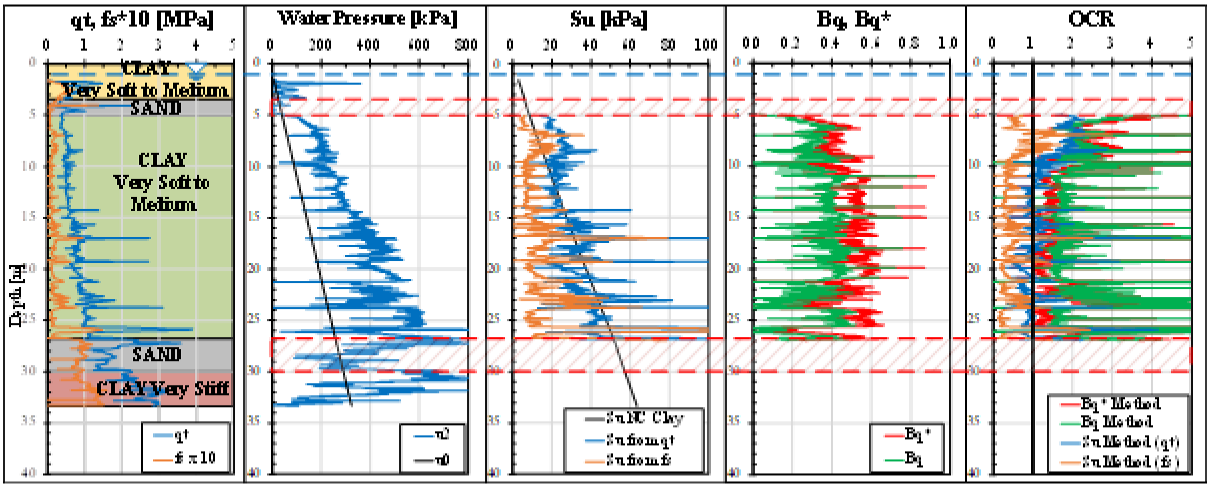


Figure 21. Result of CPTu-4 at Project 15C represents Area 4

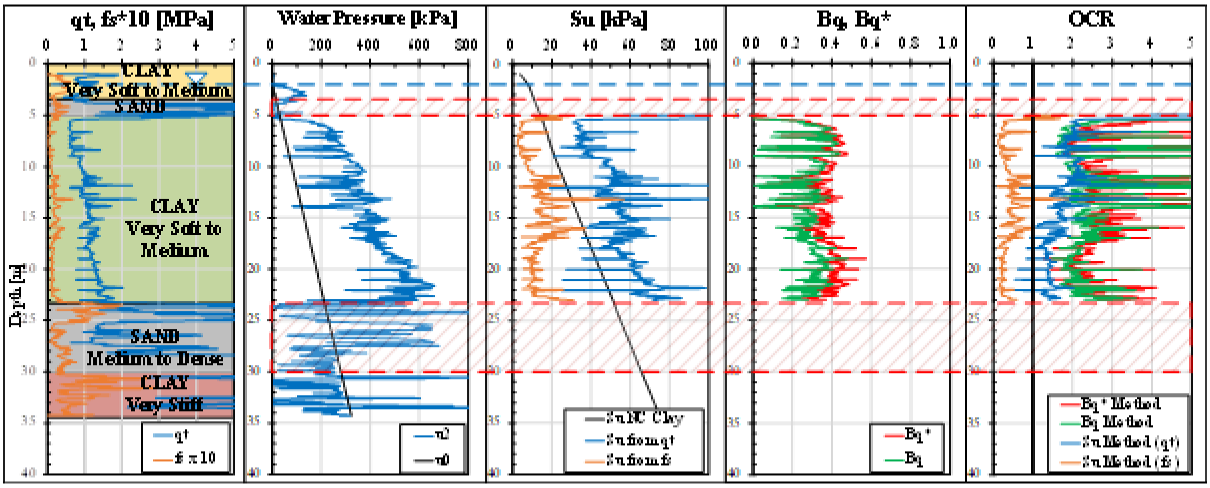


Figure 22. Result of CPTu-5 at Project 15 represents Area 4

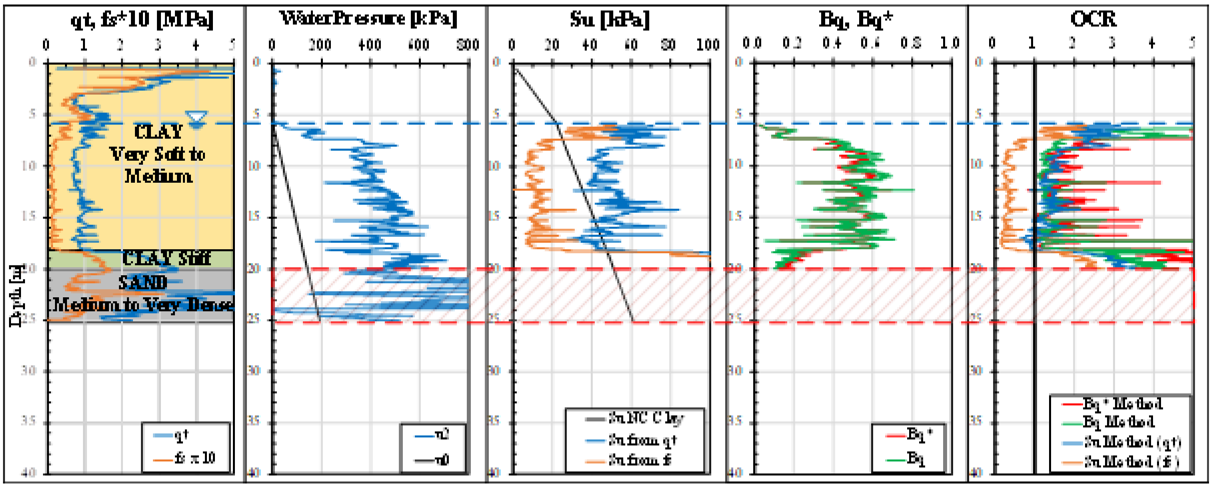


Figure 23. Result of CPTu-2 at Project 14 represents Area 5

The interpretation of the CPTu test using B_q, B_q^*, and S_u methods showed under-consolidation in some soil layers in Central Jakarta.

The soft soil in Area 3 was dominated by UC and NC, while Area 4 comprised of Lightly Overconsolidated Clay (LOC) layers. Meanwhile, some thin layers of under-consolidating samples (UC) were observed in several tests, although those in Area 5 predominantly comprised of NC and LOC.

The OCR values from the S_u the method were relatively lower than those obtained from B_q and B_q^*. The outcomes, as interpreted from f_s, were generally lower than deciphered those from q_t. This phenomenon was attributed to lower OCR produced in contrast with other methods.

4 DISCUSSION

The purpose of this research was to characterize the soft soil in Central Jakarta using the data collected from laboratory and through CPTu tests. The results generally showed a predomination of CH and MH in the soil layers of the study area.

The drilling, SPT, CPTu, and laboratory tests identified the soft soil layers at a depth of 0 to 25 m. This was indicated by a high natural moisture content, ranging from 40 to 250%. In addition, the layer has a high void ratio of 1 to 6, denoting an alluvial characteristic, although some places also possess some sand lenses amidst the composition.

The plastic limit (PL) of the soft soil layer was in the range of 25 to 120%, while the liquid limit (LL) was between 50 and 200%. Moreover, the Atterberg limit values, moisture content and the plasticity index (PI) range from 20, 10, and 110, while the liquidity index was between 0 and 3. The LI values higher than 1 were indicative of a soil sample characterized by a liquid state, and having a soft consistency.

The dry unit weight reportedly ranged from 6 to 16 kN/m^3, and values less than 10 kN/m^3 indicate under-consolidation (UC). In addition, $C_c = 2.6$ was recorded, where values greater than 1 indicates high compressibility and soft consistency. This outcome was, however, consistent with results on soil's physical properties.

The laboratory tests showed the following correlations:

$e = 8.8 \times \sigma_v'^{\,-0.357}$
$C_c = 0.4587 \times e$
$C_c = 0.0108 \times w_n$

5 CONCLUSION

The CPTu test interpretation using B_q, B_q^*, and S_u methods showed a number of soil layer samples in Central Jakarta to be under-consolidating. This outcome was predominant in Area 3, while Areas 4 and 5 comprised mostly of NC and LOC. Moreover, several tests indicated the presence of under consolidating (UC) soil in other areas.

The OCR values from the S_u method were reportedly lower than those from B_q and B_q^* methods. Particularly, those interpreted from f_s were generally lower than q_t. This phenomenon yielded the production of lower OCR values in contrast with the result obtained while using other methods. Consequently, this outcome is probably attributed to the over-prediction of the S_u determined for soft soil from q_t. The use of f_s correlation was recommended to predict undrained shear strength in soft soil.

Due to the variation of OCR values and S_u interpreted from CPTu, future studies are recommended to conduct the Vane Shear Test (VST), which aims at verifying the use of N_{kt} and S_u values. The use of case studies based on the monitoring data required in the back analysis is also suggested.

DISCLAIMER

The authors declare no conflict of interest.

AVAILABILITY OF DATA AND MATERIALS

All data are available from the author.

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