Over-consolidation Feature of Clayey Soils in Southern Vietnam According to Piezocone

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ABSTRACT: Over-consolidation ratio (OCR) is an important geotechnical parameter for predicting undrained shear strength, lateral pressure ratio and settlement of clayey ground. Based on the reliable data of consolidation test results of samples taken by piston tube and piezocone, relationship between over-consolidation ratio and normalized penetration resistant is established and analyzed. The results show that the relationship of the two quantities can be presented by linear function with coefficient k*, which ranges from 0.17 to 0.22. Using the normalized cone resistance Q_t allows analyzing behavior and stress state of over-consolidated clay more reasonable than the corrected resistance q_t.

KEYWORDS: Soft soil, Over-consolidation ratio, Piezocone, Relationship.

1. SOME RESULTS OF RELATIONSHIP BETWEEN OCR AND RESULTS OF CONE PENETRATION TEST

Predicting OCR from cone penetration test (CPT) results has been carried out since 1978. The methods of determination can be divided to 3 main groups: (i) experimental method based on undrained shear strength S_u, (ii) the method based on shape of cone resistance graph and (iii) direct method.

In 1978, Schmertmann proposed the method to estimate OCR of clayey soils based on CPT results. The method was based on undrained shear strength S_u from cone resistance q_c accounting on the concept of normalized value (SHANSHEP) to establish the relationship between S_u/σ'_{vo} and OCR.

The first studies of OCR from CPTu were presented by Baligh (1980). He found out that the more value of u_1/q_c the lower OCR. Besides, the value of u_1/q_c is reliable enough to estimate the small OCR value ($1 \leq OCR \leq 2$).

Campanella and Robertson (1981) proposed to use dynamic stress factor ($\Delta u_m/q_c$) instead of total pore pressure factor (u_m/q_c) and the pore pressure measured in position u_2 instead of position u_1. Tumay et al. (1982) suggested using $\Delta u_m/q_c$ value as an index of OCR vs. depth. These results show that the value of $\Delta u_m/q_c$ reduces when OCR increases.

The figure of CPT graphs also allows estimating pre-consolidation pressure p_c and OCR value. For normal consolidated soil, normalized cone resistance (Q_t) depends on plastic index I_p and it can be expressed as:

$$Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} = 2.5 \div 5.0 \tag{1}$$

Therefore, if the Q_t value is more than the upper bound value then it means the soil is considered over consolidated. It follows that, if the value of Q_t is close to the limited line then the soil is considered normal consolidated, if it is below the line then under consolidated and if it is above the line then over-consolidated.

Baligh (1980) has shown that the measured pore pressure during penetration can present the stress history. Then, the relationship between OCR and normalized cone resistance or normalized pore pressure can be established.

Mayne (1991) introduced the calculation method based on cone indentation and limit state theory and convinced that:

$$OCR = 2\left[\frac{1}{1.95M+1}\left(\frac{q_t - u_2}{\sigma'_{vo}}\right)\right]^{1.33} \tag{2}$$

Where: $M = \frac{6\sin\varphi'}{3-\sin\varphi'}$ - slope of critical state line.

For light over-consolidated soft clay, q_t usually has small value meanwhile u_2 has tendency to the bigger value. Hence, the value of ($q_t - u_2$) is usually small and unreasonable some times. In some cases with available test results, the correlation in formula (1) can be simplified as below:

$$Q_t = k\,\frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \tag{3}$$

Where: k = 0.2 ÷ 0.5, average of 0.3; k may be bigger in heavily over-consolidated soil (Powell et al., 1988).

OCR value plays an important role in the degree of accuracy of predicting settlement. The consolidation testing results with sampling by piston tube allow getting the more reliable OCR value which is bigger in comparison with sampling by thin walled tube. Besides, piezocone test is expensive and rarely used in investigation for small project. The established relationship of OCR value and normalized penetration resistant is the reliable data for references and allows getting the necessary characteristics for design when lack of data.

2. OVER-CONSOLIDATION FEATURE OF CLAYEY SOILS IN SOUTHERN VIETNAM ACCORDING TO PIEZOCONE

In Southern Vietnam, a thick layer of saturated soft clays distributes throughout all the area. It includes Mekong (the analyzed data was collected in Ca Mau province) and Dong Nai (the analyzed data was collected in HCMC and Vung Tau) alluvial deposits. Below the soft clayey layer, there is a layer of either stiff to very stiff clay or fine sand.

The general soil profile at Ca Mau power plant area is described as below:

- Loose fine sand. This layer has just been filled a couple of months before the soil investigation (Oct. 2013). The thickness of the layer is about 0.5 to 2.0 m.
- Layer 1 - greyish blue, blackish blue, soft clay, high plasticity. This layer is majority of alluvial marine clay (am $Q_{IV}{}^{2-3}{}_2$) with some shell and organic content. The distributed depth ranges from 15.86 m to 16.35 m. Thickness of layer 1 is about 15.4 to 16.1m and more. The properties of soil are shown in Table 1.

Table 1 Soil properties of layer 1 at Ca Mau power plant

Description	Min. Value	Max. Value
Shear strength S_u (VST) kG/cm^2	0.099	0.372
Sensitivity	1.6	9.5
Cone resistance q_c kG/cm^2	1.02	6.6
Sleeve friction f_s kG/cm^2	0.03	0.4
Cone resistance q_c (CPTu)	0.1	6.0
Sleeve friction f_s kG/cm^2 (CPTu)	0	0.14
Moisture content (W%)	68.9	
Bulk Density ρ (g/cm^3)	1.56	
Void ratio	1.917	
Specific gravity G_s	2.69	
Liquid limit (LL %)	74.4	
Plastic limit (PL %)	27.0	
Plastic index (I_p %)	47.4	
Liquid index (I_L)	0.88	
Triaxial test (UU)		
Internal friction angle (φ °)	0°11'	5°02'
Cohesion c (kG/cm^2)	0.04	0.30

- Layer 2 - Stiff to very stiff grey, brown, yellowish brown clay with some laterite. Distributed depth is from 20.35 m to 27.73 m. Thickness of this layer is about 4 to 11 m. The properties of soil are shown in Table 2.

The distribution of moisture content and bulk density of clayey soils with depth is illustrated in Figures 1 and 2 respectively.

Table 2 Soil properties of layer 2 at Ca Mau power plant

Description	Min. Value	Max. Value
Shear strength S_u (VST) kG/cm^2	0.397	2.257
Sensitivity	2.8	9.5
Cone resistance q_c (CPTu)	5	34
Sleeve friction f_s kG/cm^2 (CPTu)	0.11	1.3
Moisture content (W%)	29.6	
Bulk Density ρ (g/cm^3)	1.93	
Void ratio	0.840	
Specific gravity G_s	2.73	
Liquid limit (LL %)	60.3	
Plastic limit (PL %)	23.5	
Plastic index (I_p %)	36.8	
Liquid index (I_L)	0.17	
Triaxial test (UU)		
Internal friction angle (φ °)	2°00'	7°24'
Cohesion, c (kG/cm^2)	0.49	0.90

The general soil profile along Tan Son Nhat - Binh Loi expressway is described below:

- Filling material or light yellow sandy top soil, sand with some gravel, somewhere high plasticity clay with some organic matter. Thickness is from 0.3 to 1.2 m.
- Layer 1 - CH/MH: Very soft dark grey to blue clay or silt, high plasticity with some organic content. The thickness is to 16.7 m. The property of this layer is described below:
  Moisture content: W=91.7%, bulk density: ρ=1.47g/cm^3, specific gravity: G_s=2.66, void ratio: e=2.472, liquid limit: LL=96.0%, plastic limit PL=34.6%, plastic index I_p=61.4%, liquid index: I_L= 0.93, triaxial UU φ°=1°27', c=0.13kG/cm^2), undrained shear strength S_u (VST)=0.256kG/cm^2, compression index: C_c=1.13, re-compression index C_s=0.23, cone resistance q_c (CPT)< 0.80MPa. Below this layer is silty sand, somewhere very stiff clay.

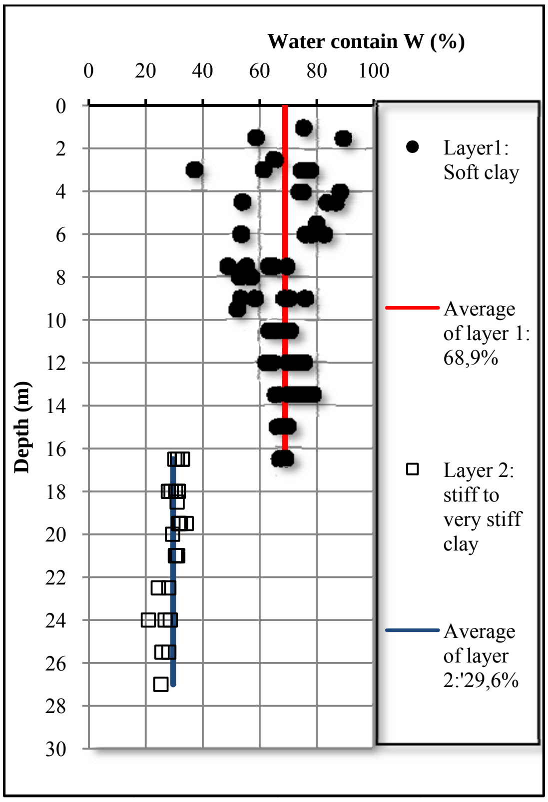


Figure 1 Moisture content of clayey soils with depth at Ca Mau power plant

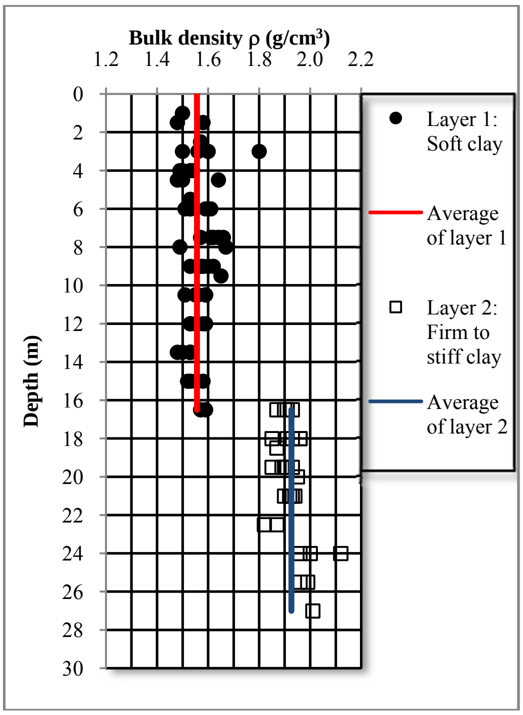


Figure 2 Bulk density distribution with depth at Ca Mau power plant

The general soil profile of Phu My Amonia factory is described as below:

- Layer 1 - Fine to medium clayey sand with some dark grey organic materials. Thickness is from 0.8 to 2 m.
- Layer 2 - Firm to stiff white grey or red brown low plasticity clay/sandy clay with some laterite. Thickness is up to 11.1 m. Soil property is summarized in Table 3.

Table 3 Soil properties of layer 2 of Phu My Amonia factory

Description \ Distribution	Min. Value	Max. Value	Average
Thickness (m)	2.4 (C135B)	11.1 (B110)	6.5
Elevation (m)	0.04 (C135B)	-7.16 (C115)	-3.31
Moisture content (%)			24.7
Specific gravity			2.71
Bulk density ρ (g/cm^3)			1.97
Void ratio e			0.714
Liquid limit (LL %)			46.0
Plastic limit (PL %)			22.0
Plastic index (I_p %)			24.0
Cone resistance q_c (MPa)	1.92	4.2	2.90
N value (SPT)	4	13	-
Internal friction angle φ	1°17'	20°17'	-
Cohesion, c (kG/cm^2)	0.27	1.02	-

The water table at investigation depth can be determined as $h_w = u_o/\gamma_w$, where: u_o – stable pore water pressure after dissipation, γ_w – unit weight of water. Dissipation test result at the depth of 5 m in Ca Mau plant shows that the water table is approximately at the ground surface and also the surface of saturated soft clay layer (Figures 3 & 4).

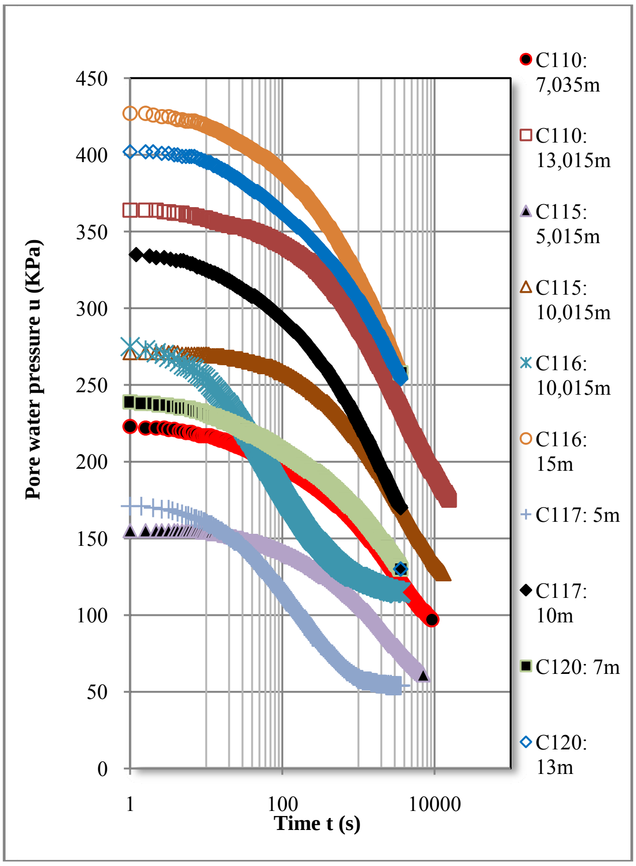


Figure 3 Dissipation in soft soil by CPTu test at Ca Mau power plant

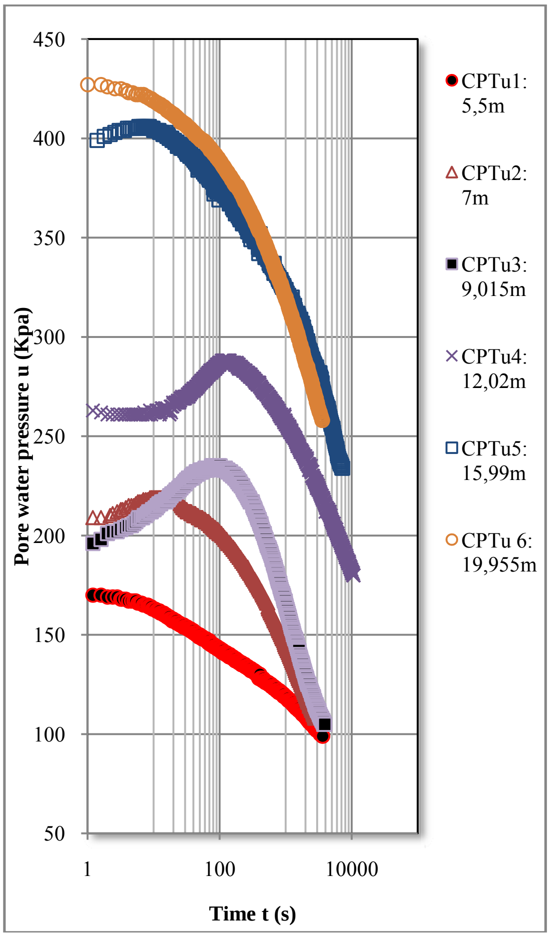


Figure 4 Dissipation by CPTu test of TSN – BL expressway project

Cone penetration test allows determining undrained shear strength S_u and close relating to soil stress history; hence, it allows estimating OCR.

One of the most important parameters in CPT result is normalized cone resistance $Q_t = (q_t - \sigma_{vo})/\sigma'_{vo}$. On the other hand, according to Houlsby (1988), correlation between S_u and OCR can be expressed as below:

$$\left(\frac{S_u}{\sigma'_{vo}}\right) = m\left(OCR\right)^{\Lambda} \tag{4}$$

Hence:

$$Q_t = \left(\frac{q_t - \sigma_{vo}}{S_u}\right) \times \left(\frac{S_u}{\sigma'_{vo}}\right) = N_{kt} \times m\left(OCR\right)^{\Lambda} = f(OCR) \tag{5}$$

Formula (5) shows that the normalized cone resistance value Q_t relates closely to over-consolidation ratio OCR and it is considered as occurrence index of OCR of clayey soil. Hence, Q_t can be expressed as a function of OCR.

Based on the mechanical and physical parameters of the laboratorial tests and oedometer test, the OCR value of saturated soft and stiff clay vs. depth is summarized and shown in Figure 1. In this case, the samples were taken by Piston sampling method in Ca Mau province. The result graph shows that the OCR value is distributed non-linear vs. depth. Near the surface, soil is considered over consolidated and the OCR value reduces with increasing depth. In soft soil, from 10m downward, soil is in normal consolidated state, the OCR value is not changed significantly and equal approximately to 1.

The relationship between Q_t and OCR is expressed by power and linear functions as shown in Figures 6 and 7 clearly. Therefore, using the value Q_t allows estimating the OCR value. There, the relationship coefficient R^2 of the linear function is higher in comparison with the power function, especially in soft soil. For suitable predicting the OCR value, the linear relationship of OCR with Q_t is established as shown in Figure 7. Moreover, the independent valuable is minimized to one.

In Ho Chi Minh City, the test results in two areas was examined and analyzed: Tan Son Nhat – Binh Loi expressway (where the road exists and at the depth to 10 m, soft clay is lightly over-consolidated due to traffic load) and Phu My Bridge (Figure 8). In addition, the analyzed data also includes the data in Phu My - Vung Tau area.

The oedometer test results show that OCR value is non-linear to the depth. As it has been pointed above, the OCR value is greater at the top and decreased by depth. In saturated soft clay layers, the non-linear distribution can be shown clearly from 10 m upward. From 10 m downward, the soil has normal consolidated characteristic (OCR ≈ 1).

More importantly, OCR value has close relationship to Q_t. In this case, the correlation is expressed as power and linear functions (Figures 9 & 10).

The non-linear relationship of OCR and normalized cone resistance can be expressed by equation:

$$Q_t = N_{kt} \times m\left(OCR\right)^{\Lambda} = S\left(OCR\right)^{\Lambda} \tag{6}$$

For saturated soft clay, the value S =(N_{kt} x m) varies from 4.48 to 6.82; value of Λ varies from 0.80 to 0.97 (Figure 5). For normal consolidated soil (OCR = 1): Q_t = S. To simplify the prediction, we suggest setting up the linear correlation of OCR by Q_t. Based on the established linear trend-line, the relationship coefficient R^2 is greater than the value based on non-linear relationship (Figure 9 and 10). It means that the linear relationship function could be more reliable.

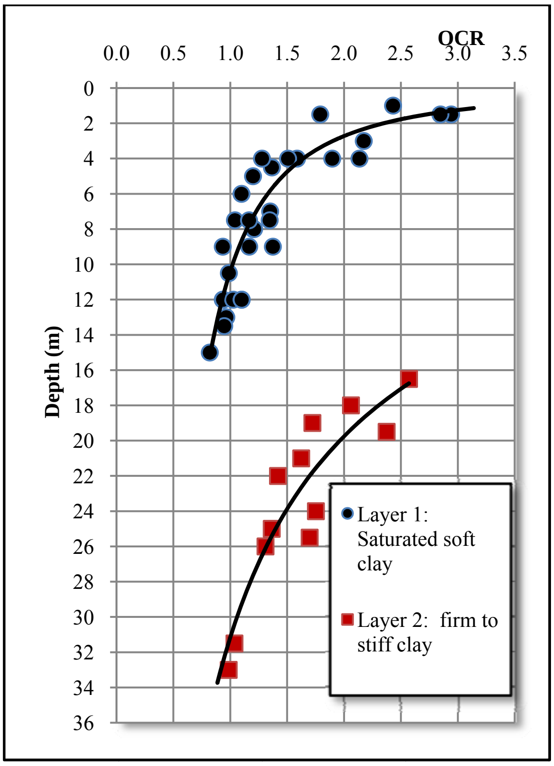


Figure 5 Value OCR vs. depth at Ca Mau power plant

Based on definition of cone penetration factor, in order to have a quick evaluation of OCR value, it is possible to establish the correlation of OCR by Q_t with the following linear function:

$$OCR = k^* \times \left(\frac{q_t - \sigma_{vo}}{\sigma'_{vo}}\right) = k^* \times Q_t \tag{7}$$

In this case, the result from statistic of correlation allow accepting k^* value for each soil type of different areas that shown in Table 4. The summary shows that the k^* value is distributed within relatively narrow range (from 0.17 to 0.22).

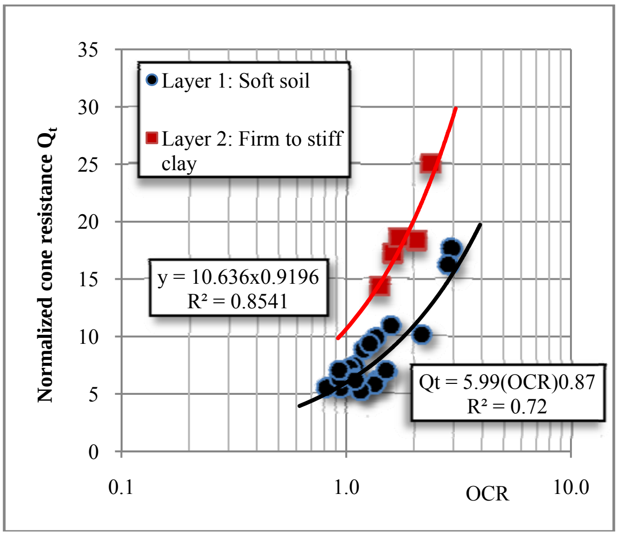


Figure 6 Power relationship of Q_t and OCR at Ca Mau power plant

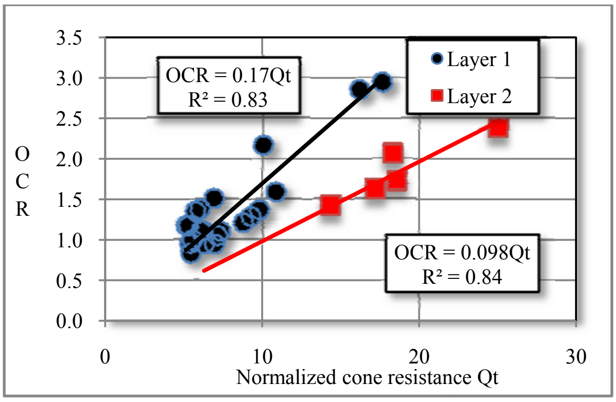
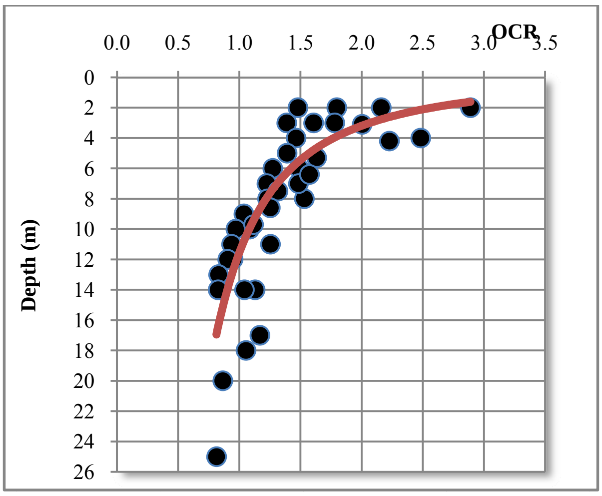
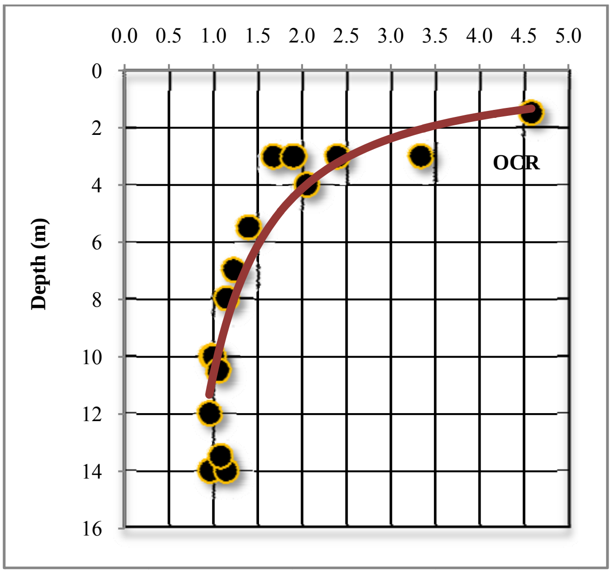


Figure 7 Liner relationship of OCR and Q_t at Ca Mau power plant



(a)



(b)

Figure 8 OCR vs. depth distribution graph of soft clay in TSN-BL express way (a) and Phu My Bridge (b)

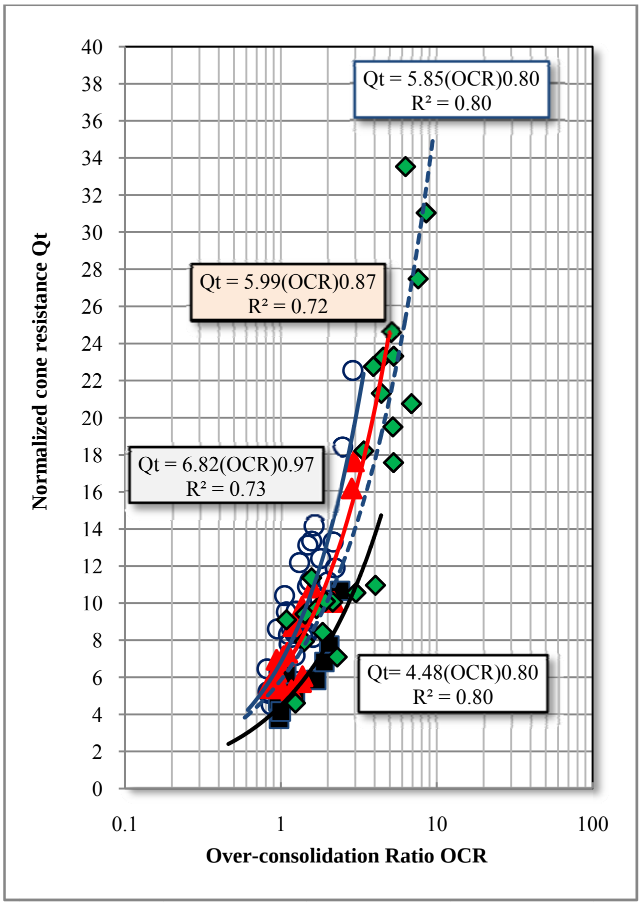


Figure 9 Power relationship of Q_t and OCR in different areas

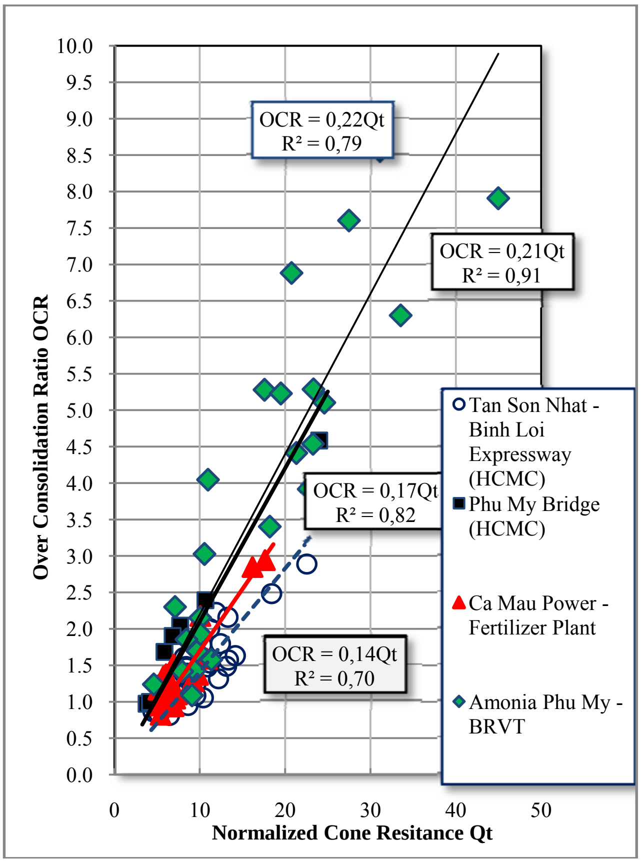


Figure 10 Linear relationship of OCR and Q_t in different areas

Table 4 Summary of relationship coefficients between OCR and Q_t in different areas

Nº	Project	Soil type	**k* value**	Location
1	Ca Mau Power Plant	Very soft clay (ρ=1.56g/cm^3; W=68.9%)	**0.17**	Ca Mau province
2	TSN – BL Expressway	Very soft clay (ρ=1.47–1.57g/cm^3; W=61.9-91.7%)	**0.14**	HCMC
3	Phu My Bridge	Very soft clay (ρ=1.56g/cm^3; W=68.9%)	**0.21**	HCMC
4	Phu My Amonia Factory	Stiff to very stiff clay (ρ=1.97g/cm^3; W=24.7%)	**0.22**	Ba Ria Vung Tau province

In order to evaluate the reliability and applicability of k^* value, the normalized cone resistance was back-analyzed from OCR with available k^* based on established correlation. The back-analyzed Q_t value and its original value was plot in Figures 11 and 12 for comparison.

It is also noted that the q_t value varies insignificantly in one soil layer even though the OCR (due to self-weight) has significant varying along the depth. Meanwhile, Q_t varies noticeably follow the depth and much depends on compressibility of soil which is represented by OCR value. Therefore, using value Q_t in CPTu allows evaluating soil stress history, soil behavior as well as better soil classification.

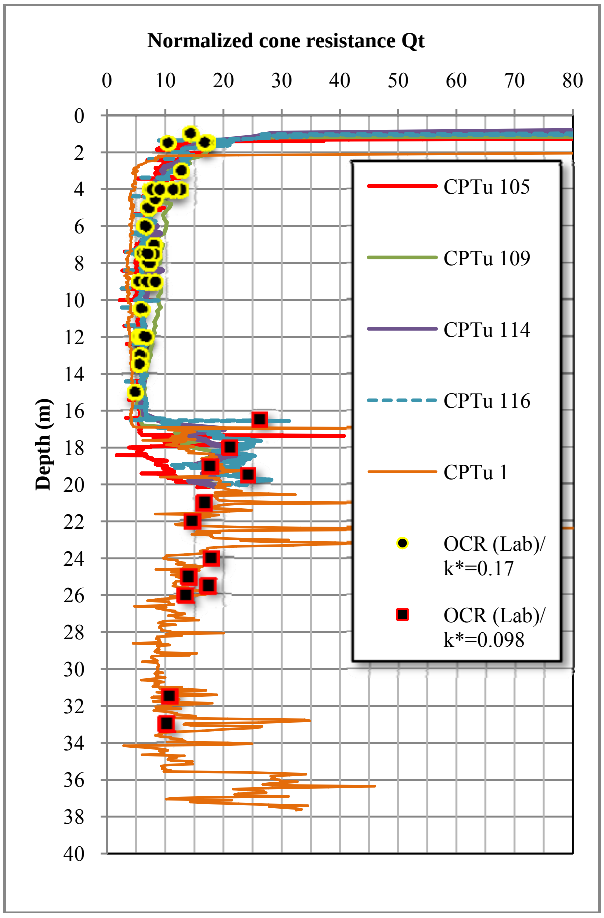


Figure 11 Q_t vs. depth from CPTu and correlated value from OCR and k^* in Ca Mau

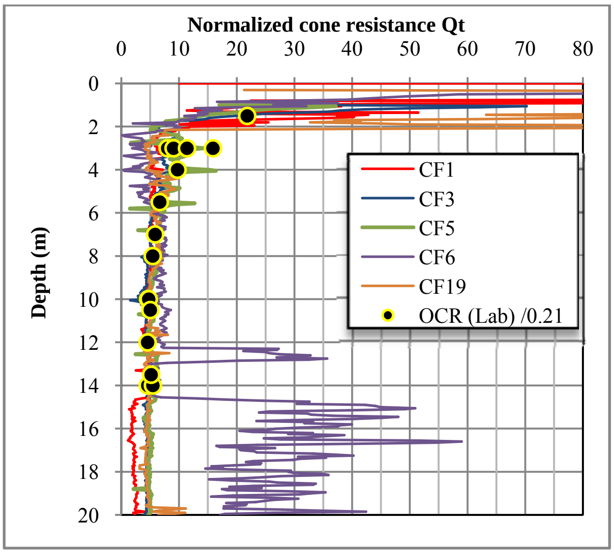


Figure 12 Q_t vs. depth from CPTu and correlated value from OCR and k^* in Phu My Bridge (HCMC)

3. CONCLUSION

Based on laboratorial test results and piezocone test results of various specific projects in Southern areas of Vietnam, the correlation between OCR and Q_t was analyzed. The results lead to the following conclusions:

- For saturated soft clay, the normalized cone resistance and OCR is correlated clearly by non-linear function. In which, S = (N_{kt} x m) value varies from 4.48 to 6.82; Λ value varies from 0.80 to 0.97.
- Correlated over-consolidation ratio (OCR value) of soil from different areas from Q_t value was distributed with narrow range of k^* value from 0.17 to 0.22. In the area, where embankment exists, the value k* may be smaller.
- The evaluation of relationships among OCR and Q_t as well as N_{kt} allows determining factor of m and Λ in SHANSEP formula. For saturated soft clay, m = 0.375 and Λ varies from 0.87 to 0.97.

Recommendation of using Q_t instead of q_t in CPTu due to its comprehensibleness on stress state and behavior.

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