International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:10, No:7, 2016

Developing a New Relationship between Undrained Shear Strength and Over-Consolidation Ratio

Wael M Albadri, Hassnen M Jafer, Ehab H Sfoog

***Abstract*—**Relationship between undrained shear strength (Su) and over consolidation ratio (OCR) of clay soil (marine clay) is very important in the field of geotechnical engineering to estimate the settlement behaviour of clay and to prepare a small scale physical modelling test. In this study, a relationship between shear strength and OCR parameters was determined using the laboratory vane shear apparatus and the fully automatic consolidated apparatus. The main objective was to establish non-linear correlation formula between shear strength and OCR and comparing it with previous studies. Therefore, in order to achieve this objective, three points were chosen to obtain 18 undisturbed samples which were collected with an increasing depth of 1.0 m to 3.5 m each 0.5 m. Clay samples were prepared under undrained condition for both tests. It was found that the OCR and shear strength are inversely proportional at similar depth and at same undrained conditions. However, a good correlation was obtained from the relationships where the R2 values were very close to 1.0 using polynomial equations. The comparison between the experimental result and previous equation from other researchers produced a non-linear correlation which has a similar pattern with this study.

***Keywords*—**Shear strength, over-consolidation ratio, vane shear test, clayey soil.

I. Introduction

IN geotechnical design practice, the most two important concerns that require careful inspection are whether construction will cause deformation of the soil and/or instability caused by shear failure. Therefore, an engineer must be sure that the structure is safe against shear failure in the soil supporting it and does not experience excessive settlement [1]. For over consolidated clay where the maximum past effective stress is greater than the present effective stress ($P_c > P'_v$), the calculation settlement may involve either one of two following cases which depend on Pc,P′ and surcharge value (ΔP). If the $P_c \geq ((P'_v + \Delta P))$, the consolidation settlement is determine using (1):

$$Sc = (H_o/1 + e_o)\ Cr \log ((P'_v + \Delta P) / P'_v) \tag{1}$$

where: Sc = consolidation settlement; H_o = totalheight of the clay layer; e_o=void ratio; Cr =rebound index; P'_v = vertical effective stress; ΔP = surcharge value. While for the $Pc < (P'_v + \Delta P)$, (2) is used to determine the settlement:

$$Sc = (H_o/1+e_o)\ [Cr \log ((P'_v + \Delta P) / P'_v) + C_c \log ((P_c + \Delta P)/P'_v)] \tag{2}$$

where: P_c = Pre-consolidation; C_c = Compression Index.

As a result, P_c is an important parameter to determine which equation should be used in order to determine the settlement value [2]. The effective stress pressure underneath a ground surface could be estimated well if Su ratio could be determined from the standard penetration test (SPT) [3].

Effendi and Sheahan et al. used the relationship to prepare their ground model using a clay material for a small scale physical modelling test. A reliable and accurate method should be used to establish relationship between Su and consolidation ratio. Besides that, the use of the relationship is important in preparing a ground model in small scale physical modelling [4], [5].

Several researches have been conducted to establish relationship between Su and OCR for clay material (marine clay) [3], [5]-[7]; and different density on sand [8] respectively. Nunez [3] and Springman [6], [7] determined the Su value using the vane shear test on marine clay model made by consolidated the marine slurry; while Philips and Valsankar [8] used a penetrometer to obtain the strength of the sand. A series of triaxial tests was conducted by Sheahan et al. to investigate the stain rate effect on Su under different OCR value [5].

II. Material Properties

In order to establish relationship between shear strength and OCR, the physical properties have to be identified so that the proposed correlation in this study shall be utilized only for the soil that having same soil properties of this study and to evaluate soil characteristics if it is suitable of compression characteristics of marine clay soil. Table I shows the summery of the physical properties of the samples of soil.

TABLE I
Physical Properties of Marine Clay Used in This Study

Soil Properties	Value
Liquid Limit	42.86
Plastic Limit	33.27
Plasticity index	15.29
Soil type	CL
Specific gravity	2.64

Wael M. Albadri is MSc Geotechnical Engineer, Civil / Geotechnical Engineering, Tun Hussein Onn Malaysia UTHM University, Malaysia (phone: 009647715442317; e-mail: w_m120@yahoo.com).

H. M. Jafer is Postgraduate Research Student, Liverpool John Moores University, School of the Built Environment (phone: 00447448938628; e-mail: H.M.Jafer@2014.ljmu.ac.uk).

Ehab H. Sfoog is MSc Geotechnical Engineer, Civil / Geotechnical Engineering, Tun Hussein Onn Malaysia UTHM University, Malaysia (phone: 009647823860385; e-mail: ehab_sf@yahoo.com).

Based on the British standards BS1377-2-1990 (Fig. 1), and by utilizing the data in (Table I), marine clay was classified as CL (Clay Low Compressibility).

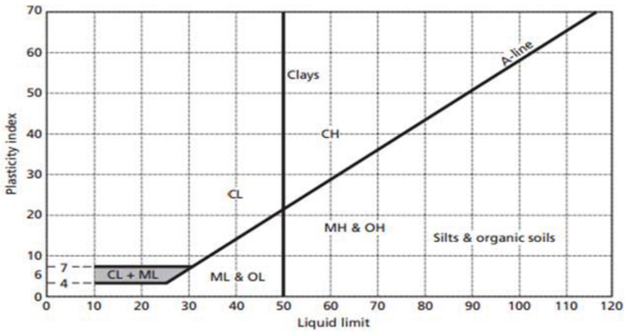

Fig. 1 Plasticity Chart: British System (BS 1377-2:1990)

III. Experimental Works and Results

A. Pre-Consolidation Pressure

The pre-consolidation pressure is defined as the maximum past effective overburden pressure to which the soil specimen has been subjected. It can be calculated by using a simple graphical procedure introduced by Casagrande (1936). The procedure summarized in five steps by [8] as shown in Fig. 2 are:

a. Identify the point O on the curve which has the smallest radius of curvature
b. Draw a horizontal line OA.
c. Draw a line OB that is tangent to the curve at O.
d. Draw a line OC that bisects the angle AOB.
e. Develop the straight-line portion of the curve backwards to intersect OC. This is point D. The pressure that corresponds to point D is the pre-consolidation pressure.

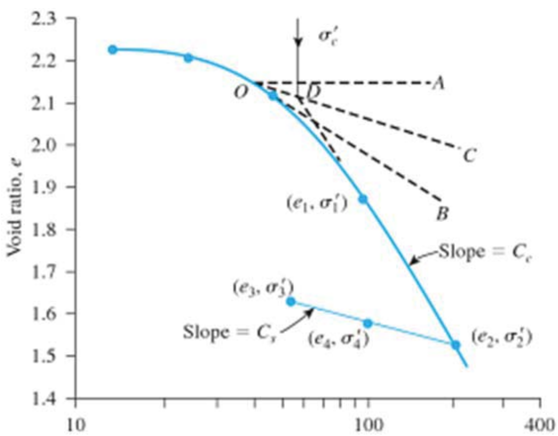

Fig. 2 Graphical Procedure of Consolidation

Fig. 3 shows the relationship between void ratios and logarithm of the consolidation pressure curves on the primary settlement only for the data obtained from the results of consolidation test. The consolidation characteristics of the soil during pre-consolidation of the marine clay were obtained.

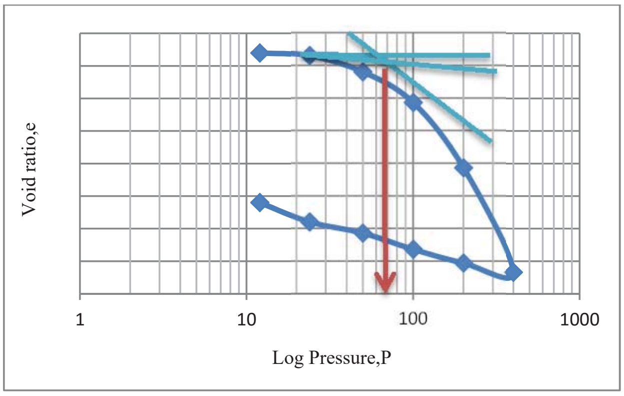

Fig. 3 Consolidation Curve (Fully Automatic Consolidated) Based on Pre-Consolidation a Typical e-log p Curve

It was found that the value of compression index (C_c) was around 0.09 and the coefficient of volume compressibility (m_v) equals to 1.3 cm^2/kN. This parameter is used to estimate the primary consolidation settlement. Results of point (1) for OCR are listed in Table II.

TABLE II
OCR Results

Depth(m)	Effective stress pressure, p'_v (kN/m^2)	Pre-consolidation pressure, p_c (kN/m^2)	OCR
1	5.57	22	3.58
1.5	8.97	23	2.56
2	12.68	24	1.89
2.5	16.36	32	1.95
3	21.16	35	1.65
3.5	25.23	42	1.66

Marine clay is sensitive to the effect of disturbance, which can influence the relationship between void ratio and pressure (e-log p curve) derived from consolidation test on (a fully automatic consolidated). Hence, extreme care is needed in the preparation of test specimen. The e-log p ' curve derived from undrained consolidation test was constructed from data in which the comparison is due to primary settlement.

B. Su

The test is conducted to measure the Su of the fine-grained soil in accordance to BS 1377: Part 9: 1990. The laboratory test can be performed on undisturbed samples; Fig. 4 shows some of the undisturbed samples.

The structural strength of soil is basically a problem of shear strength. Vane shear test is a useful method for measuring shear strength of clay; it is suitable for the sensitive soil and can also be conducted in the laboratory. Degree of deformation can be used to find the torque value and the value of diameter and height of vane were 0.012 m and 0.019 m which can be used to calculate the Su as:

$$Su = \frac{T}{\pi(\frac{H.D^2}{2}+\frac{D^3}{6})} \quad (3)$$

By applying the equation above, shear strength can be determined as shown in Table III.

Fig. 4 Undisturbed Samples

TABLE III
SHEAR STRENGTH VALUES

Depth(m)	Degree of deflection	Torque,T (kN.m)	Su, S_u (kN/m^2)
1	17.11	5.19E-05	10
1.5	19.05	6.19E-05	11.91
2	26.51	7.15E-05	13.76
2.5	27.31	7.57E-05	14.56
3	29.21	7.77E-05	15.95
3.5	32.1	8.39E-05	16.15

C. Correlation between Shear Strength and Consolidation Ratio

Once the results of shear strength and OCR are obtained, correlation between these two terms can be easily constructed. This correlation can be conducted by arranging the obtained data in excel sheet then the curve and equation that link the shear strength and consolidation can be constructed for each borehole as shown in Fig. 5.

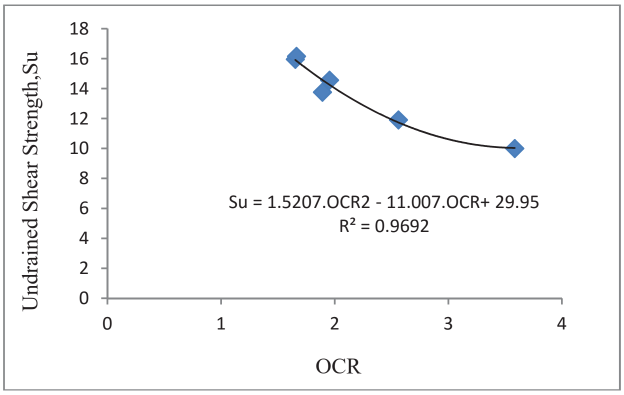

Fig. 5 Relationship between Su and OCR for Borehole (1)

The final equation can be obtained by taking the average of the correlation for three boreholes which can be ascertained from the strength of the relationship through precision if approached accuracy (R^2) to one. Fig. 6 shows the average of the correlations of three boreholes. To obtain better correlation with higher accuracy, the scope of the study has to be greater than this study, in other word, the number of samples must be more than 18 sample.

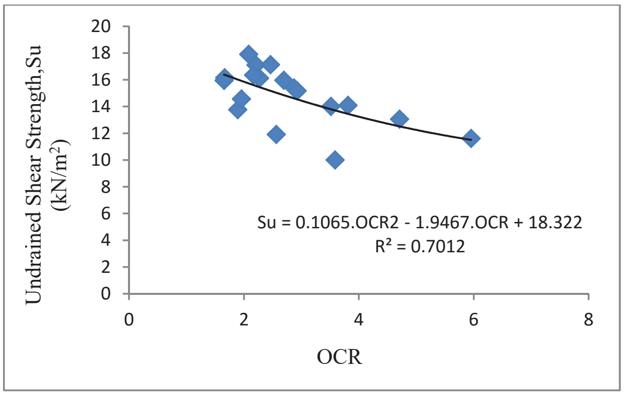

Fig. 6 Relationship between Su and OCR for Average of Three Boreholes

The obtained relationship was compared with the previous studies in order to verify the correlation obtained from this study (Fig. 7).

Ladd and Foott have introduced a relationship between the ratio ($\frac{Su}{P'v}$) and OCR [9], (4):

$$\frac{Su}{P'v} = a.OCR^b \quad (4)$$

where: P'_v is vertical effective pressure, (a) and (b) are parameters, the value of the parameters (a) and (b) have subjected to variety of changing according to different previous studies Table IV.

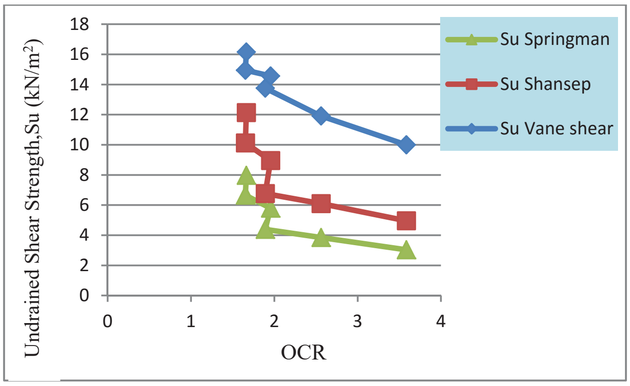

Fig. 7 OCR Values Versus Su from This Study (Vane Shear Test) and Previous Studies for Borehole 1

TABLE IV
SHEAR STRENGTH VALUES

Name	a	b
Springman 1989 [6]	0.22	0.71
Shansep 1987 [8]	0.32	0.8

The data of undrained strengths measured using direct simple shear tests for the various soils all show a similar trend of increasing values of Su/P'v with OCR. The same trend is seen when the Su is measured using other types of tests.

Similar to previous studies, this study has determined its own values of (a) and (b), the obtained relationship was compared with the previous studies (Fig. 8).

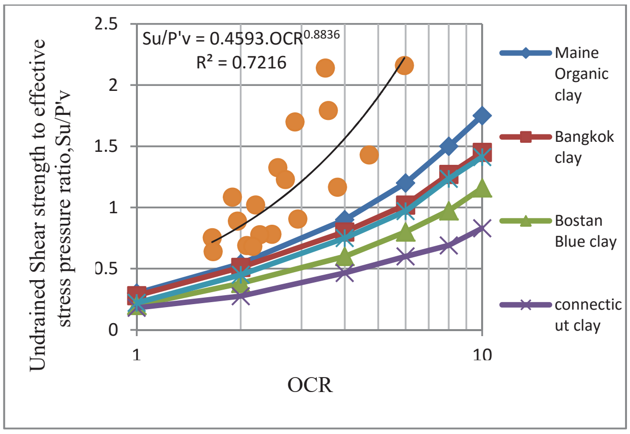

Fig. 8 Comparing the Relationship in Terms of the Parameters (a) and (b) for this Study and Previous Studies [6], [8]

The difference between previous studies and the obtained relationship was because of the difference and testing approach since the shear strength can be determined by using vane shear test, shear box, unconfined compression test etc. Second reason for that difference is the sampling and sample preparations, some errors might occur during sampling and sample preparation which may lead to difference in results, third reason, is the number of samples, the accuracy of the results increase with the increase of the number of samples.

IV. Conclusion

Based on the analysis carried out, the conclusion of the study can be summarized as follow:

1. From the values shown in Table III, the value of Su is increased with increase of depth.
2. OCR values of clay soil are inversely proportional with the Su from vane shear test of soil samples. That is mean; OCR values will decrease with the increasing of the Su.
3. The nonlinear correlation of shear strength and OCR of this study where: Su = 0.1065.OCR2 - 1.9467.OCR + 18.322. This correlation was verified by comparing it with previous study.
4. The parameters of the correlation of this study, a and b were 0.46 and 0.88 according to (4).
5. There are small different in correlations between previous studies and this study. These differences came from changing in behaviour of soil according to type of soil, and from type of the test used to get the Su (shear box, unconfined compression test, traixail test and vane shear test).

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