SHEAR STRENGTH CHARACTERISTICS OF RESIDUAL SOILS FROM SEDIMENTARY JURONG FORMATION IN SINGAPORE

by

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Shear Strength Characteristics of Residual Soils from Sedimentary Jurong Formation in Singapore

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SYNOPSIS: Residual soils from sedimentary Jurong Formation is widely found over the island of Singapore. In this study, field and laboratory data collected from more than 300 boreholes drilled at 14 sites located in Western Singapore were analysed and general co-relation between the undrained shear strength, s_u, the effective cohesion intercept, c', and the effective angle of shearing resistance, ϕ', and their corresponding influence factors such as SPT N-value, dry unit weight, clay content, Plasticity Index and initial degree of saturation are established for engineering design reference. Comparisons between the estimated and tested shear strength parameters of residual soils from other sites were also studied and discussed.

INTRODUCTION

Highly heterogeneous mixed granular and cohesive deposits, which may in addition be partially saturated, are commonly encountered worldwide, and variously referred to as residual, saprolithic and indurated soils. In Singapore, more than two-thirds of the land area (Figure 1) is covered by residual soils (Pitts, 1984). These residual soils are the products of in-situ physical and chemical weathering of bedrock consisting of mudstone, sandstone, shale, conglomerates and siltstone as well as granite, adamellite and granodiorite etc. in Singapore's tropical climatic condition. Due to the rapid development on the island, there is an increasing number of major projects that involve natural residual soils. For instance, in the western part of Singapore Island there are several construction projects underway on its undulating terrain, which is underlain by the residual soil of the sedimentary Jurong Formation. Each of these projects involves a large amount of earthwork, foundation work and site development in the residual soils.

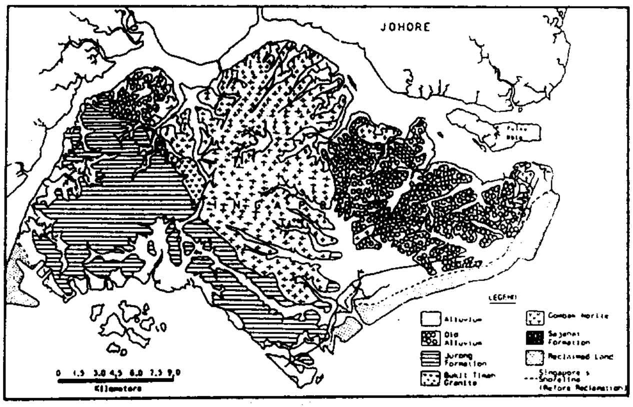

Fig. 1 Geological Map of Singapore (Based on Geology of the Republic of Singapore by PWD 1976)

A review on the available literatures shows that limited work has been done on residual soils in Singapore. On the basis of laboratory and field test results from two major projects in Central Singapore, Poh et al. (1985) found that the undrained shear strength, s_u of the granite residual soil increased with depth, the effective cohesion intercept, c' increased with clay content and the effective angle of shearing resistance, ϕ' decreased with clay content. In 1985, Yong et al. intended to study engineering properties of the residual soils of the sedimentary Jurong Formation in Western Singapore through consideration of effect of partial saturation. However, no general co-relation between s_u, c', ϕ' and their corresponding influence factors had been concluded by Poh et. al. (1985) and Yong et al. (1985). In 1994, Zhao & Lo proposed an empirical approach for the undrained shear strength, s_u for design of foundations in three major residual soils, i.e. Old Alluvium Formation, sedimentary residual soil and granite residual soil. Through their studies, Zhao & Lo (1994) pointed out that s_u had a simple linear relationship with SPT-N value. The linear coefficient between s_u and SPT-N value could be as high as 7.00 for the Old Alluvium Formation, 5.70 for the sedimentary residual soil and 5.25 for the granite residual soil. The high linear coefficients could be partially attributed to the effect of partial saturation in the in-situ undisturbed specimens. More recently, Lim (1995), Han et al. (1995), Rahardjo, Chang & Lim (1995) and Rahardjo et al. (1995) have investigated the general properties of residual soils particularly from the sedimentary Jurong Formation at the Nanyang Technological University in Jurong area of Western Singapore and also studied the effect of rainfall on slope stability in residual soils. Rahardjo, Chang & Lim (1995) and Rahardjo et al. (1995) have incorporated the shear strength theory for unsaturated soils (Fredlund et al., 1978) to evaluate the contribution of matric suction on shear strength and pointed out that the effect of partial saturation on shear strength is considered to be very significant. However, they had not presented any general co-relation between s_u, c', ϕ' and their corresponding influence factors that can be very valuable to the practical engineering design.

Although some research mentioned above has been conducted on Singapore residual soils, the shear strength characteristics of in-situ residual soils of the Jurong Formation are still not well understood. In recent years, extensive site investigation together with laboratory and field testing had been carried out in the Jurong Formation at Western Singapore. More than 300 boreholes were drilled in the sedimentary residual soils at more than 14 sites and over a period of more than ten years. Standard Penetration Tests (SPT) were conducted at each borehole in frequent intervals to obtain the so called N values and undisturbed soil samples were obtained for laboratory testing.

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Numerous unconsolidated undrained triaxial compression (UU) tests and multi-stages consolidated undrained triaxial compression ($\overline{\text{CIU}}$) tests with pore water pressure measurement were conducted on undisturbed soil samples. On the basis of the results of these tests, attempts to study the effects of a number of factors on s_u, c' and ϕ' were made. Relationships between s_u and SPT-N, dry unit weight, γ_d or clay content, confining pressure, σ_3 and initial degree of saturation, S, and relationships between c', ϕ' and SPT-N and clay content, C have been established. Some empirical equations for the estimation of s_u, c' and ϕ' of residual soils of Jurong Formation are proposed for design reference.

RESIDUAL SOILS IN SINGAPORE

The residual soils of Jurong Formation in Singapore are well described in the Geology of Singapore (PWD, 1976). The sedimentary residual soils are generally derived from weathering of its sedimentary parent rocks consisting of mudstone, sandstone, shale, conglomerates and siltstone which had been subjected to considerable tectonic activity in the geological past, thereby results in extensive folding and faulting. The sedimentary residual soils generally tend to exhibit an increasing degree of compaction with depth due to a corresponding decrease in the degree of decomposition. Results of X-ray diffraction analyses indicate the presence of plagioclase felspar, quartz, mica, kaolinite, montmorillonite and chlorite (Yong et al., 1985; Parashar, 1994). The predominant clay mineral in the residual soils is kaolinite.

In Singapore, the sedimentary residual soils have undergone the primary weathering stage where the resultant soil is mainly sandy clayey silt. In some locations, a layer of reddish brown sandy silty clay can be found above the clayey silt. The reddish colouration and the presence of laterite within this silty clay layer indicate that secondary weathering of the residual soils is more advanced at shallow depth and progressively becomes less intense with depth as indicated by the increase in grain size.

IN-SITU AND LABORATORY TESTING

The soils investigated here are mainly from 14 sites underlain by the Jurong Formation at Western Singapore. A total of more than 300 boreholes were drilled to different depths and rotary wash boring was carried out for all the sites as more representative undisturbed samples and more reliable in situ tests could be obtained. During drilling, Standard Penetration Tests (SPT) and split spoon sampling were carried out in accordance with BS5930 at about 1.5m to 3.0m intervals or at changes of subsoil strata excluding depths where undisturbed sampling was carried out. Representative samples were taken from the split spoon sampler for classification tests. Undisturbed samples were obtained by using thin wall and thick wall tube samplers. The physical properties tests consisting of moisture content, bulk density, specific gravity, Atterberg Limits and grain size distribution (i.e. hydrometer tests and sieve analyses) were conducted on undisturbed soil samples and split spoon linear samples for soil classification.

To determine the shear strength characteristics of the sedimentary residual soils, numerous undisturbed samples have been tested directly in unconsolidated undrained triaxial compression (UU) test and in multi-stages consolidated undrained triaxial compression ($\overline{\text{CIU}}$) test with measurement of pore water pressure.

ENGINEERING CHARACTERISTICS OF RESIDUAL SOILS

General Physical Properties

The measured Liquid Limits, w_L are generally between 23 to 107 (Figure 2) with average value of 50 ± 11 and Plastic Limits, w_p are between 12 to 38 with average value of 24 ± 4. The water content and Plasticity Index, I_p of the residual soils generally decrease with depth. The Plasticity Index ranges from 8 to 75. Therefore, these residual soils are of low to high plasticity. The clay content (i.e., percent finer than 0.005mm) for the fine grained residual soils ranges from 6% to 69% with average value of 34.6 ± 11.3% (Figure 3). The actual grain size distribution of the residual soils varies from site to site as a result of differential weathering and differences in composition of its highly stratified parent material. The specific gravity varies from 2.47 to 2.84 with average value of 2.69 ± 0.03. This value is higher than those of quartz, kaolinite, and felspar because of the presence of iron materials due to laterization. The total and dry unit weights range from 15.20 kN/m^3 to 21.73 kN/m^3 with average value of 19.09 ± 0.86 kN/m^3 and from 10.45 kN/m^3 to 19.08 kN/m^3 with average value of 15.35 ± 1.29kN/m^3, respectively. The residual soils are generally partially saturated with measured degree of saturation ranging from 53% to 100%. The measured Over-Consolidation Ratio, OCR varies generally from 1.04 to 4.94 with average value of 2.70 ± 0.82 that indicates clearly that the sedimentary residual soils are in over-consolidated state. The measured SPT-N value of the residual soils generally increases with depth and varies from 1 to over 100 Blows per 300mm penetration.

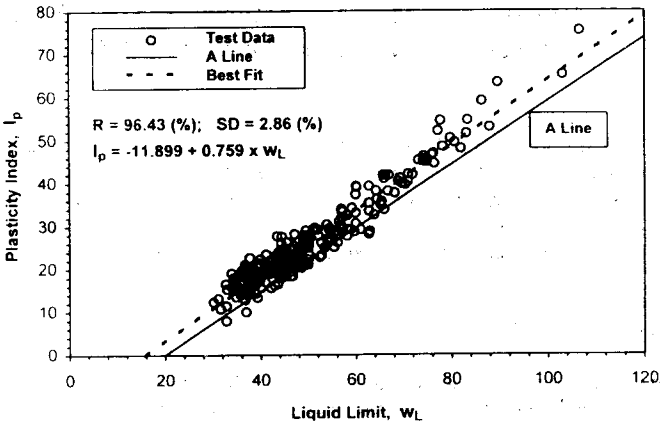

Fig. 2 Plot of Liquid Limit versus Plasticity Index

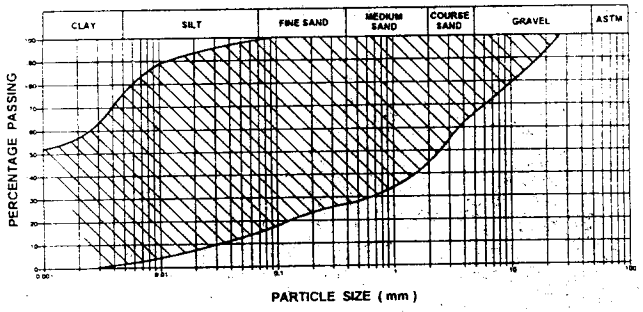

Fig. 3 Grain Size Distribution of the Residual Soils

In general, the sedimentary residual soils can be classified as very soft to stiff sandy/silty clay in upper zone to stiff to very stiff sandy/clayey silt in middle zone to very dense silty/clayey sand with rock fragments in bottom zone right above the bedrock. Figure 4 presents a relationship between Plasticity Index, I_p and clay content, C (%) that shows I_p increases with clay content. The degree of plasticity of the residual soils is much dependent on the presence of clay particle and can be expressed as

$$I_p = 12.160 \times EXP(1.956 \times C / 100) \quad (1)$$

The coefficients in Eq. (1) were estimated by using the best-fitting technique.

In Figures 5 and 6, the dry unit weight of the residual soils presents a clear trend of decreasing with increasing of clay content or Plasticity Index and of increasing with increasing of SPT-N value. In general, the dry unit weight, γ_d (kN/m^3) of residual soils increases with depth as the SPT-N value increases and clay content decreases with depth. By using the best-fitting technique, the dry unit weight of the residual soil can empirically be expressed as :

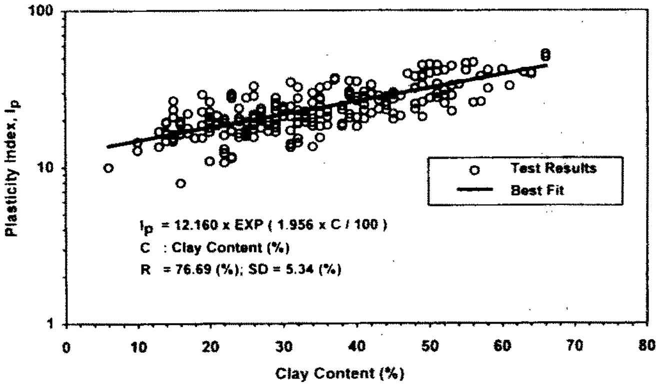

Fig. 4 Plot of Plasticity Index versus Clay Content

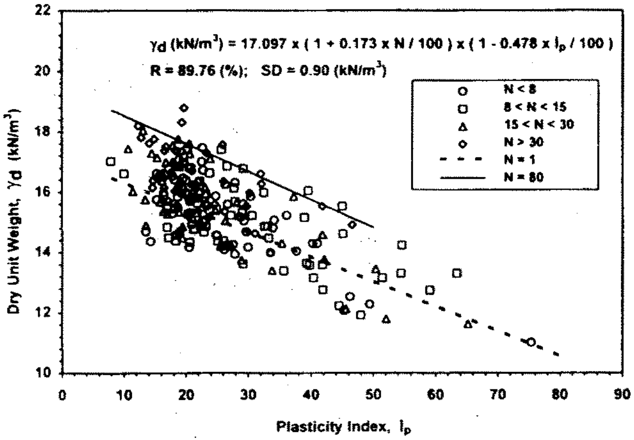

Fig. 5 Plot of Dry Unit Weight versus Plasticity Index

$$\gamma_d = 17.097 \times (1 + 0.173 \times N / 100) \times (1 - 0.478 \times I_p / 100) \quad (2)$$

$$\gamma_d = 16.216 \times (1 + 0.210 \times N/100) \times (1 - 0.0182 \times C^{1.6974}/100) \quad (3)$$

Undrained Shear Strength (s_u)

It is well established in the literatures that SPT - N values are in some measures directly related to the undrained shear strength (Terzaghi & Peck, 1948; Schultze & Knausenberger, 1957; Sowers, 1954; de Mello, 1971; Zhao & Lo, 1994). Before attempting to investigate this co-relation in detail, it is important to understand that there are other factors related to the undrained shear strength. The results of tests show that the undrained shear strength increases with SPT - N value in an power form and increases with dry unit weight in an exponential form but decreases with clay content in an exponential form. Besides the above-mentioned three factors, the confining pressure and the initial degree of saturation may also be the two other factors with significant influence on the unsaturated specimen. As we known, the shear strength of unsaturated soils can be expressed as (Fredlund et al., 1978; Fredlund and Rahardjo, 1993)

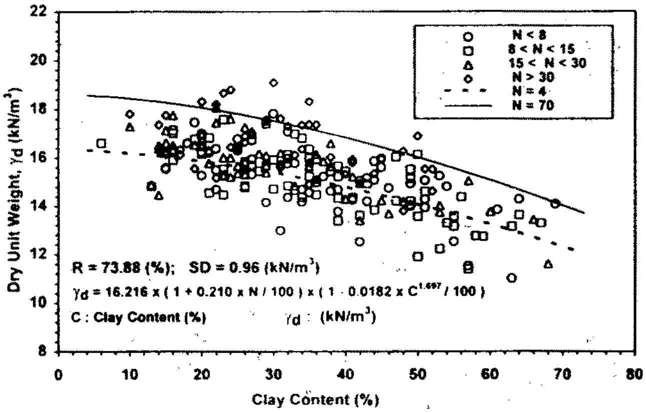

Fig. 6 Plot of Dry Unit Weight versus Clay Content

$$\tau_{ff} = c' + (\sigma - u_a)_f \tan \phi' + (u_a - u_w)_f \tan \phi^b \quad (4)$$

where τ_{ff} is the shear stress on the failure plane at failure, c' is intercept of the "extended" Mohr-Coulomb failure envelope on the shear stress axis where the net normal stress and the matric suction at failure are equal to zero, it is also referred to as effective cohesion intercept, $(u_a - u_w)_f$ is matric suction on the failure plane at failure, u_a is pore air pressure, u_w is pore water pressure, $(\sigma - u_a)_f$ is net normal stress on the failure plane at failure, ϕ' is effective angle of shearing resistance associated with the net normal stress variable $(\sigma - u_a)_f$ and ϕ^b is angle indicating the rate of increase in shear strength relative to matric suction, $(u_a - u_w)_f$.

Based on Eq. (4), the additional undrained shear strength, Δs_u due to unsaturation in unsaturated soils can be considered to be attributed to the effect of matric suction $(u_a - u_w)$. The matric suction $(u_a - u_w)$ in an unsaturated soil increases generally with decreasing of degree of saturation. Therefore, the additional undrained shear strength due to unsaturation can be considered to increase generally with decreasing of degree of saturation. On the other hand, the confining pressure σ_3 applied to an unsaturated specimen can compress and densify the soil so as to consolidate the sample and finally increase the shear strength. Therefore, the additional shear strength due to confining pressure in an unsaturated specimen can be considered to increase generally with the magnitude of confining pressure. However, due to the complication of the problem, no mathematical or empirical equation are available up to date for describing the coupled effect of confining pressure, σ_3 and initial degree of saturation, S on the undrained shear strength, s_u. The following Eq. (5) is an empirical equation for describing the coupled effect of SPT-N value, dry unit weight, γ_d (kN/m^3), confining pressure, σ_3 (kN/m^2) and initial degree of saturation, S (%) on s_u.

$$\begin{aligned} s_u = {} & 20.417 + 44.774 \times (N^{0.5} / 100) \times EXP(1 + 14.220 \times \gamma_d / 100) \\ & + 52.086 \times [1 + 0.915 \times (\sigma_3 / 98.1)] \times [EXP(1) - EXP(S/100)]^{0.581} \end{aligned} \quad (5)$$

where the coefficients in Eq. (5) were estimated by using best-fitting technique. From Figure 7, the coefficient of co-relation between the s_u

and the influence factors, R is computed to be 76.64%. This value appears to be slight low but can still be considered to be reasonable. Since some influence factors like the structure of the in-situ undisturbed soils, sample disturbance, sample spatial dispersity and Over-Consolidation Ratio, etc. have not been incorporated into the analyses.

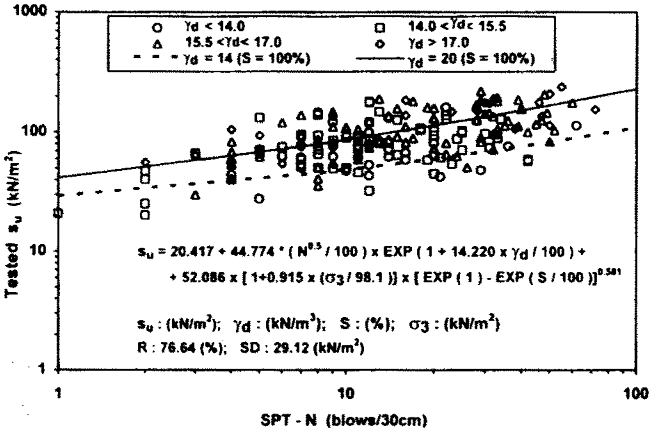

Fig. 7a Plot of Tested s_u versus SPT - N & Dry Unit Weight

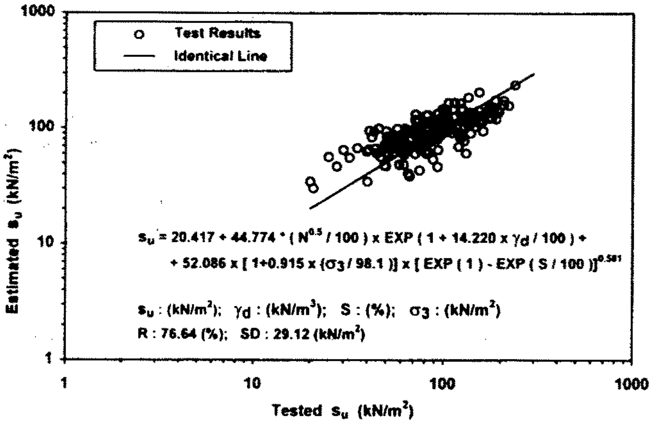

Fig. 7b Plot of Estimated s_u versus Tested s_u

The second part of Eq. (5) represents the effect of confining pressure and initial degree of saturation on the s_u (Figure 8). From Eq. (5), the s_u increases with increasing of confining pressure (before full saturation) and decreasing of initial degree of saturation. Eq. (5) indicates also clearly that s_u increases with increasing of SPT-N value and dry unit weight. Since from Eq. (3) the dry unit weight decreases with increasing of clay content, therefore the s_u decreases also generally with increasing of clay content.

Effective Shear Strength Parameters (c', ϕ')

To analyse the effective shear strength parameters, c' and ϕ' in the same way as do for the s_u, similar empirical equations can also be established by best-fitting technique as

$$c' = -4.035 + 4.009 \times EXP\{1.095 \times [LOG(N+0.01)]^{0.745}\} \times EXP(0.00135 \times C) \quad (6)$$

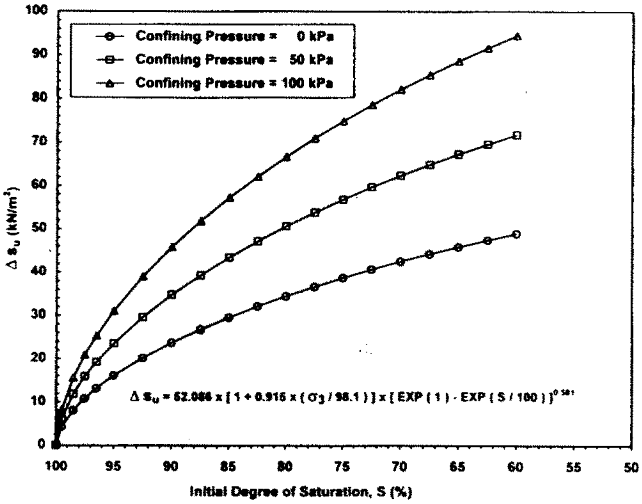

Fig. 8 Plot of Additional Undrained Shear Strength Due to Unsaturation versus Initial Degree of Saturation and Confining Pressure

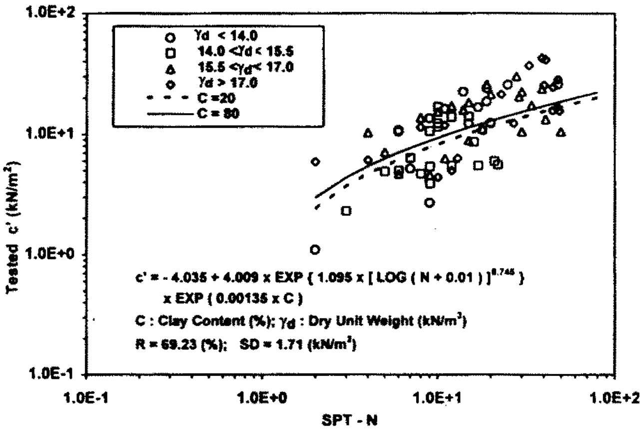

Fig. 9a Plot of Effective Cohesion Intercept versus SPT - N and Clay Content

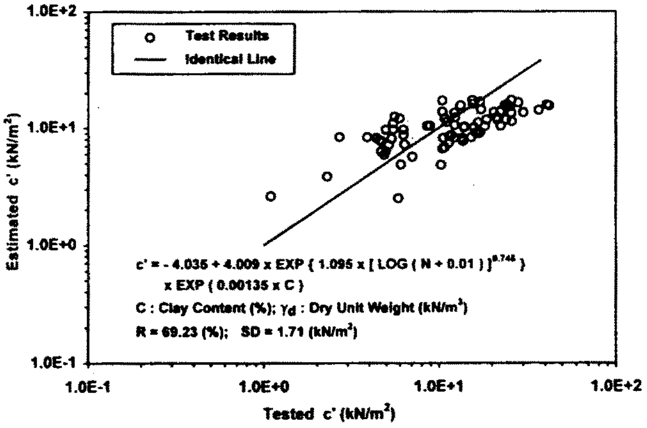

Fig. 9b Plot of Tested Effective Cohesion Intercept versus Estimated Effective Cohesion Intercept

$$\phi' = 32.352 \times (1 + 0.314 \times N / 100) \times (1 - 0.316 \times C / 100) \qquad (7)$$

From Figures 9 and 10, the coefficients of co-relation between c', ϕ' and factors SPT-N and clay content, C (%) are analysed to be 69.23% and 70.54%, respectively. The reasons for the low calculated coefficients of co-relation between the c', the ϕ' and the influence factors can be similar to that for the s_u.

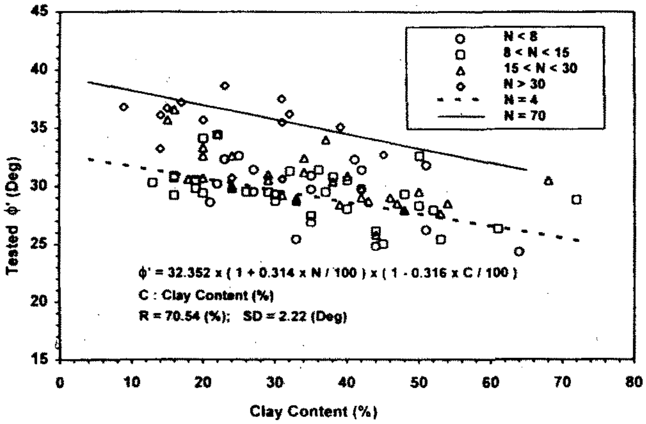

Fig. 10a Plot of Effective Angle of Shearing Resistance Versus Clay Content and SPT - N

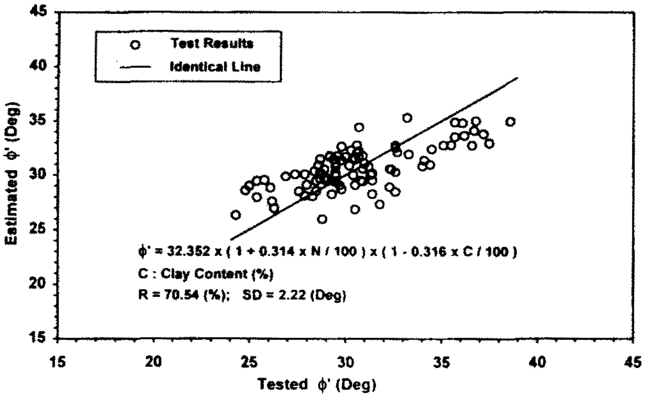

Fig. 10b Plot of Tested Effective Angle of Shearing Resistance Versus Estimated Effective Angle of Shearing Resistance

In general, the c' increases mainly with increasing of SPT-N values but increases slightly with increasing of clay content. The ϕ' generally increases with increasing of SPT-N values but decreases with increasing of clay content. The tested c' appears to be high for dense soils (i.e. high SPT-N) as well as high plastic soils (i.e. high clay content). The tested ϕ' shows low value for high plastic soils (i.e. high clay content) and loose soils (i.e. low SPT-N).

COMPARISONS BETWEEN ESTIMATED AND TESTED VALUES OF SHEAR STRENGTH PARAMETERS (s_u, c', ϕ')

In order to evaluate the reliability and applicability of the established empirical equations for the shear strength parameters (s_u, c' & and ϕ') of the sedimentary residual soils, comparisons between the estimated values and tested results have been made for four recent project sites, i.e., Site A to Site D as presented in Figures 11 to 13.

As indicated in Figure 11, the estimated value of s_u appears to be quite compatible with the test data. From Figures 12 and 13, the estimated value of c' and ϕ' can be considered to be reasonable as compared with the test data except for some points from Site A and Site B which show large discrepancies due to possible effects attributed to special structure of residual soil and/or sample disturbance and so on. Although difficulties and complication exist in the determination of in-situ shear strength, comparisons made above show clearly that the established general co-relation between s_u and SPT-N value, dry unit weight, γ_d or clay content, C, confining pressure, σ_3 and initial degree of saturation, S as well as the co-relation between c', ϕ' and SPT-N value and clay content, C can reasonably describe the in situ shear strength characteristics of sedimentary residual soils from Jurong Formation in Singapore.

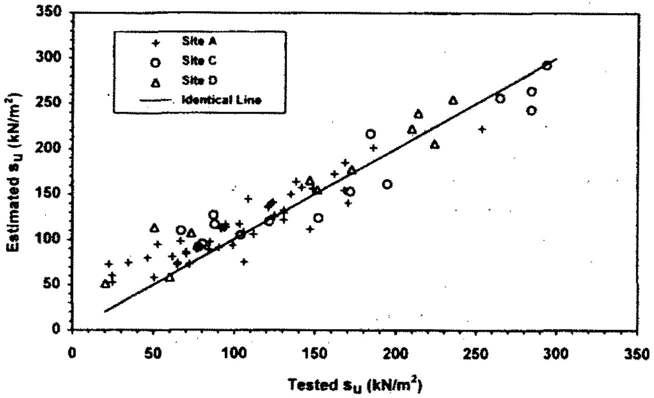

Fig. 11 Comparison of Estimated s_u with Tested s_u

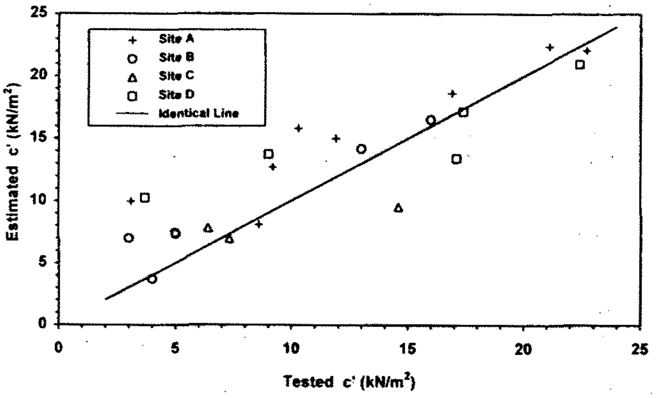

Fig. 12 Comparison of Estimated c' with Tested c'

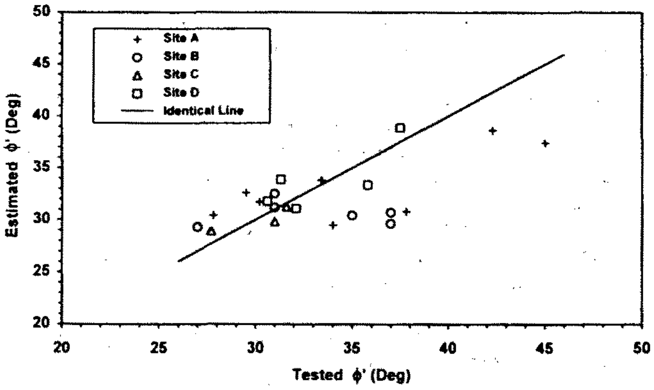

Fig. 13 Comparison of Estimated ϕ' with Tested ϕ'

CONCLUSIONS

The main conclusions of this study are as follows:

1. On the basis of the physical properties and shear strength parameters of the residual soils of sedimentary Jurong Formation available in the present study, the fundamental factors related to shear strength characteristics could basically be the dry unit weight, clay content and Plasticity Index as well as many other factors like initial degree of saturation and confining pressure applied in the test and SPT-N value.
2. The undrained shear strength, s_u of residual soils increases with increasing SPT N-value, dry unit weight and confining pressure (before full saturation) and decreasing of initial degree of saturation and clay content.
3. The effective cohesion intercept, c' increases mainly with increasing of SPT N-value but increases slightly with increasing of clay content. The effective angle of shearing resistance, ϕ' generally increases with increasing SPT N-values but decreases with increasing of clay content.
4. Empirical equations for s_u, c' and ϕ' based on physical properties and SPT N-values have been established for engineering design reference. Reasonable estimation could be achieved by using the established empirical equations, and the selection of design value should be made with the application of sufficient engineering judgement taking into consideration of actual site condition and particular requirements for certain specified development.
5. Further study to incorporate the influence of other factors, such as the structure of the in-situ undisturbed soils, sample disturbance, sample spatial dispersity and over-consolidation ratio, etc, in the empirical equations are recommended.

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