

Shear Strength Due to Unsaturated Conditions for Vacuum Consolidation Works

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ABSTRACT

Vacuum Consolidation is a soil improvement technique that applies vacuum pressure to the soil which will create a negative pore-water pressure that will produce suction in the soil mass. The suction will then cause change in volume, increase in density, increase of shear strength and stability to the soil mass of the treated area. The objectives of this project were to study the effects of suction pressures on shear strength of soils and to propose ranges of suction pressure for vacuum consolidation works in Malaysia. SoilVision Version 1.0 software was used to analyse sixteen (16) soil samples by predicting their soil-water characteristic curves (SWCC) and shear strength curves based on the particle-size data. The results of the particle-size distribution curves, the soil-water characteristic curves and the variation of shear strength with soil suctions are presented. The results show that the rate and the total increment of shear strength with respect to the soil suction are influenced by the air-entry value (AEV) and the value of effective angle of friction (Φ'), respectively. As for the case study of Deep Water Port Project in Sarawak, the results show that the increment of shear strength with respect to suction contributes about 23.9% to 29.2% of the total increment of the shear strength; the rest comes from the effect of the consolidation of the soil layers. The ranges of vacuum pressures with respect to the desired shear strength for soils of various effective angles of friction are also proposed for vacuum consolidation works.

1.0 Introduction and Objectives of the Study

The shear strength of a soil is required for addressing numerous problems, such as the design of foundations, retaining walls and pavements in civil engineering applications. The shear strength in saturated soil is common and easy to obtain. Assessing shear strength in unsaturated soil, however, is complicated, which involves other components such as soil-water characteristic curve (SWCC). One application of the knowledge of unsaturated shear strength is the application of the vacuum pressure for vacuum consolidation works. In situation and condition where conventional surcharge preloading consolidation method fails to meet the requirement in time and may cause instability to the soil mass, 'vacuum preloading consolidation' turns out to be a better option to effectively consolidate the soil, increases its strength and produces stability to the soil mass. In the design of a vacuum system for the vacuum consolidation

works, the primary concern is to achieve a good seal between the edges of the membrane and the ground so as to achieve the maximum suction possible. Current technology has eliminated the problem of poor sealing between the edges of the membrane and the ground. However, no design consideration has been given to the optimum suction to be used in order to achieve the maximum soil strength improvement. It is implicitly assumed that a higher suction will lead to a greater water loss in the soil and thus corresponding strength gain will be higher. Thus, the assessment of soil strength improvement should be performed first and the results should then be used to assess the feasibility of using vacuum preloading on a particular soil.

The objectives of this study were to estimate the shear strength with respect to soil suction for Malaysian soils and to determine the ranges of suction pressures with respect to various effective angles of friction (Φ') for vacuum consolidation works in Malaysia.

2.0 Literature Review

2.1 Unsaturated shear strength

Classical soil mechanics has emphasised specific types of soils. Textbooks cover the theories related to these types of soils in a completely dry or a completely saturated condition. Recently, it has been shown that attention must be given to soils that do not fall into these common categories. Many of these soils can be classified as unsaturated soils (Fredlund et al., 1997). For example, many practical problems of slope stability involve assessing the shear strength of unsaturated soil. Several procedures have been proposed in the literature for the past ten years to predict the shear strength of unsaturated soils. These procedures use the soil-water characteristic curve as a tool either directly or indirectly along with the saturated shear strength parameters, c' and Φ' , to predict the shear strength function for an unsaturated soil (Vanapalli et al., 1998). Fredlund and Morgenstern (1976) showed that the fundamental properties of unsaturated soil can be described by any two or three

stress state variables, namely $(\sigma - u_a)$, $(\sigma - u_w)$, $(u_a - u_w)$, where σ is the total stress, u_w is the pore-water pressure, and u_a is the pore-air pressure. Subsequently, Fredlund et al. (1978) had proposed a relationship to explain the shear strength of unsaturated soils in terms of two independent stress state variables as shown in Equation 1.

$$\tau = c' + (\sigma_n - u_a) \tan \Phi' + (u_a - u_w) \tan \Phi^b \quad (1)$$

where:

- τ =the shear strength;
- c' =the cohesion;
- Φ' =the internal friction angle; and
- $\tan \Phi^b$ =the rate at which the shear strength increases with respect to the increase of the matric suction, $(u_a - u_w)$.

2.2 Vacuum consolidation

Vacuum Consolidation method was first introduced by Dr Kjellman at the Royal Geological University in Sweden in 1952 (Mohamedelhassan et al., 2002). The principle of the vacuum consolidation is that it applies a vacuum depressurisation effect to the soil mass and reduces the pore water pressure while maintaining a constant total stress (Yee and Tan, 2001). When the total stress is the same, a change in pore water pressure will cause a change in effective stress. Thus when the pore water pressure decreases, the effective stress increases in the case of a constant total stress. This results in an increase in the soil strength and a decrease in the soil volume (Yee and Tan, 2001). The vacuum consolidation method is best applied in conditions which are: soft and saturated clay soil with extremely low shear strength, where surcharge fill is lacking, or the soft soil is adjacent to critical slopes and have easy excess to power supply (Shang et al., 1998).

3.0 Methodology

The analyses for the study were based on basic soil properties data, i.e., particle size distribution (sieve test data), Atterberg Limits, relevant weight-volume relationship/parameters [e.g. dry density (γ_d) and moisture content (w), and effective saturated shear

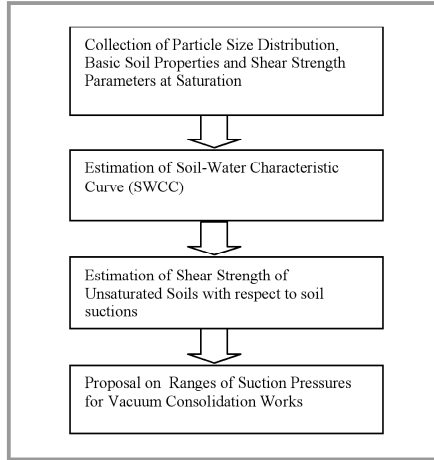


Figure 1: Flow chart for the sequences of the study

strength parameters; c' and Φ']. These data were collected from these, research report and available site investigation reports. The main analyses were carried out using SoilVision software with the input data for the estimation of the soil-water characteristic curve and the unsaturated shear strength with respect to soil suctions based on Fredlund et al. (1996). Based on the results of the relationship between the shear strength and the soil suctions, ranges of vacuum pressure with respect to shear strength requirement were proposed. The flow chart for the sequences of work is given in Figure 1.

4.1 Prediction of shear strength with respect to soil suction ($U_a - U_w$)

The input data for sixteen soil samples were used to run the analyses in Soil Vision. The SoilVision software determines the soil-water characteristic curve (SWCC) before the shear strength at various soil suctions is predicted. Figure 2 shows the particle size distribution curve and the corresponding predicted SWCC for sample TP01 before its shear strength with respect to soil suctions is calculated. The air-entry value (AEV) for TP01 is about 400 kPa (an air-entry value of a soil is a suction at which the soil starts to desaturate).

Figure 3 shows the relationship between the shear strength and the soil suction for a total of sixteen samples of the study. The broken and the full lines represent the residual soils (ranging from sand to silty sand or sandy silt with Φ' of 18° to 38°) and clay soils of Φ' of 5° to 24°,

Table 1: The increment of shear strength at 100 kPa suction for sample TP01, KML01 and SSR01 with respect to various Φ' values

Sample	Φ'	Increment of shear strength at 100 kPa suction
TP01	5°	8.4 kPa
KML01	22°	26.0 kPa
SSR01	38°	47.0 kPa

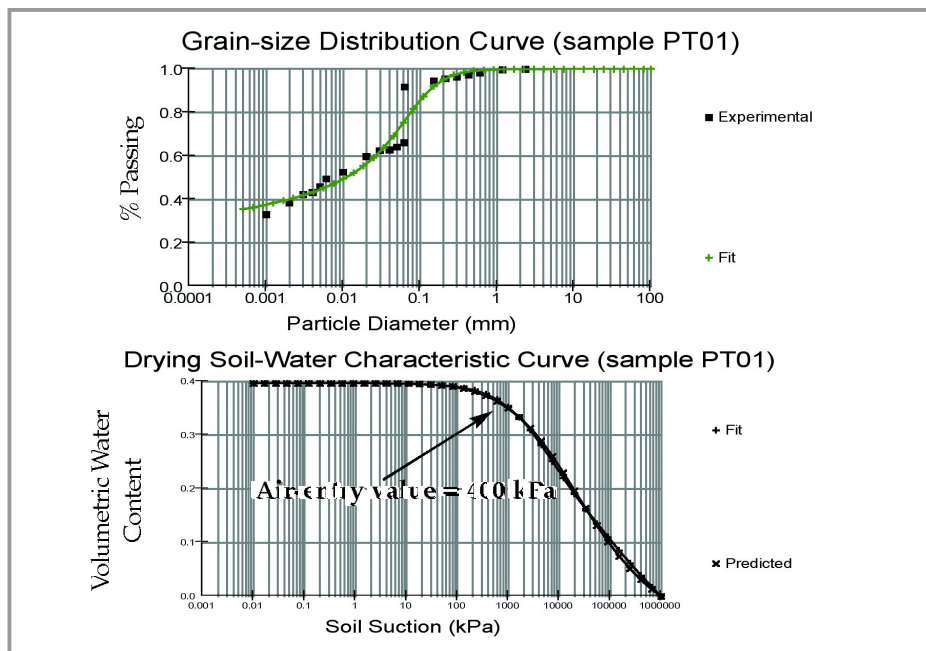


Figure 2: The particle size distribution curve of sample TP01 with its corresponding predicted SWCC with respect to the soil suctions

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respectively. The shear strength curves for all soil samples, except TP01, exhibit both 'boundary effects' and 'transition' zones for the range of 0 to 150 kPa suctions. For this range of suctions, TP01 exhibits the 'boundary effects' zone only because its 'transition' zone would only appear after its air-entry value, 400 kPa.

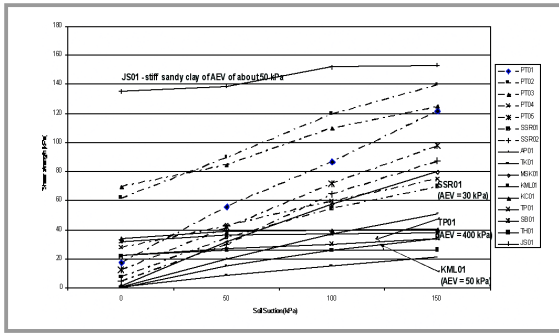


Figure 3: The result on the relationship between the shear strength and the soil suction for a total of 16 samples

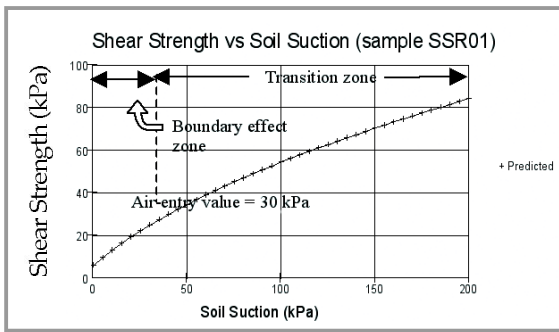


Figure 4: The boundary effect and transition zone in the shear strength plot for sample SSR01

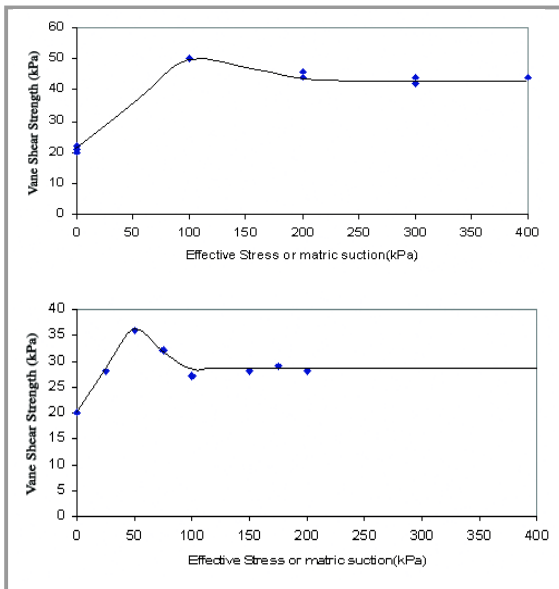


Figure 5: The vane shear strength with respect to soil suction for (a) intermediate stiff clay and (b) marine clay of Kallang formation Singapore (Redrawn from Leong et al., 2000)

The shear strength variation with respect to the soil suctions is linear at low soil suctions, at which it is called the boundary effect zone, where the suctions are less than the air-entry value (AEV). The shear strength contribution due to suction, $\tan \Phi^b$, however, is less than $\tan \Phi'$ in the transition zone. Hence, the shear strength variation in this transition zone is non-linear. The two different zones (boundary effect and transition zones) for sample SSR01 are shown in Figure 4. Beyond the maximum point of the transition zone, the shear strength gradually drops to a shear strength value at saturation as shown in Figure 5 (Leong et al., 2000). In other words, vacuum preloading is effective only up to the point of maximum strength gain in the transition zone. The reduction in the shear strength beyond this point has been attributed due to the desaturation of the soil at higher matric suction values [(Gan and Fredlund (1996) and Vanapalli et al (1996)].

The results in Figures 3 to 5 indicate that the rate and the total increment of the shear strength with respect to the suctions are influenced by the air-entry value and the value of effective angle of friction, Φ' , respectively. The comparisons of the shear strength increment for three samples with different Φ' values are given in Table 1.

This can be explained by using the unsaturated shear strength formula as stated in Equation 1. From Equation 1, the value of the shear strength with respect to the soil suction ($u_s - u_w$) is characterised by the value of Φ^b . The value of Φ^b is related to the value of Φ' . Generally the value of Φ^b is the same as Φ' at saturation or at low suction,

which is less than the air-entry value of soil. When the suction increases in the soil, the Φ^b value decreases and becomes less than Φ' (Tekinsky et al., 2004).

4.2 Case Study at Kampung Senari, Sarawak

The sample data obtained from the Deep Water Port Project in Kampung Senari, Kuching was used as a case study. After running the analyses on five samples, namely KSS01 – KSS05, the results of the increment of the shear strength at soil suction of 60 kPa were compared to the increment of the field shear strength obtained in the project as shown in Table 2.

In the case study of Kampung Senari, Sarawak, the design of vacuum pressure in vacuum consolidation work is based on the surcharge needed for the consolidation in order to obtain the desired settlement. The height of

Table 2: The increment of the shear strength at soil suction of 60 kPa obtained from the Soil Vision software

Sample	Shear Strength at Suction (kPa)		Strength Increment	Field Shear Strength Increment for Case Study 12 kPa – 19 kPa (Yee and Tan, 2001)
	0 kPa	60 kPa		
KSS01	8.1	12.3	4.2 kPa	
KSS02	9.9	13.4	3.5 kPa	
KSS03	13.5	17.8	4.3 kPa	
KSS04	9.9	14.4	4.5 kPa	
KSS05	11.7	16.0	4.3 kPa	

surcharge is then translated to an equivalent pressure to be induced upon the soil. For this case, the 60 kPa vacuum pressure was used to act as a 3 m fill of surcharge. The increment of shear strength registered at the end of the vacuum consolidation work was considered purely from the consolidation mechanism. From the analyses for the sample data of the case study, increments of shear strength of 3.5 kPa to 4.5 kPa were obtained for an increase of soil suction of 60 kPa. In comparison with the recorded increment of the field shear strength of 12 kPa to 19 kPa for the case study, the increment of the shear strength with respect to the soil suction contributed 23.7 % to 29.2 % of the total increment. In other words, the rest of the total increment of the shear strength was contributed by the effects of the consolidation of the soil layers.

4.3 Proposal on vacuum pressure for various range of soil

In a typical design of vacuum pressures in vacuum consolidation works, the design focuses on the settlement. The magnitude of pressure applied is chosen in order to achieve the desired settlement. In this paper, the authors propose ranges of vacuum pressures with respect to the required increment of the shear strength due to the soil suctions. The proposed vacuum pressures are based on the effective angles of friction (Φ') of the soils. The proposed vacuum pressures for Malaysian soils with respect to the desired shear strength values are shown in Table 3.

Table 3: Proposed vacuum pressures for the required increment of shear strength

Range of Φ' value (degree)	Increment of shear strength desired (kPa)		
	5	10	15
	Proposed vacuum pressure (kPa)		
0 - 10	65	115	185
10 - 20	25	60	100
20 - 30	15	30	50
30 - 40	10	20	30

5.0 Conclusions and Recommendations

5.1 Conclusions

The conclusions drawn from the study are as follows:

1. The shear strength variation with respect to suction is linear at lower soil suction, i.e., in the boundary effect zones. While in the transition zone, the shear strength variation is non-linear. The shear strength then gradually decreases at high values of soil suctions and subsequently reaches residual condition. The trend or rate of the shear strength function with respect to soil suctions is influenced by the air-entry value (AEV) of soils. The total increment of shear strength with respect to the soil suction, on the other hand, is influenced by the angle of internal friction, Φ' .
2. In comparison with the recorded increment of the field shear strength of 12 kPa to 19 kPa for the case study at Kampung Senari, Sarawak, the increment of shear strength with respect to the soil suction contributed

23.7% to 29.2% of the total increment. In other words the rest of the total increment of shear strength was contributed by the effects of the consolidation of the soil layers.

3. Ranges of vacuum pressures to achieve shear strength requirement had been proposed with respect to Φ' values of soils. The given increment of shear strength at a specific pressure from the proposal is a portion of the total shear strength increment for a vacuum consolidation work. As a result from the vacuum pressure applied, the consolidation process of the soil will cause the shear strength to increase to a higher value.

5.2 Recommendations

The study focuses on the prediction of the relationship between shear strength and soil suction via software analyses. For future study, experimental determination of the relationship between the shear strength and the soil suctions is recommended. Researchers are suggested to determine the Φ^b for Malaysian soil through laboratory testing and therefore further explain the relationship between Φ^b and Φ' for Malaysian soils. The field and laboratory characterisation and prediction of the shear strength with respect to soil suctions are of importance in the study of slope stability and stabilisation. ■

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