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Unsaturated Strength Behaviour and Prediction for Silty Sand

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ABSTRACT

Shear strength properties of unsaturated soils are important in evaluating the stability of geotechnical structures such as natural slopes, embankments, retaining walls, excavations and footings. This importance has been highlighted recently in Victoria, where intense rainfalls caused the massive instability of natural and man-made slopes. This study provides comprehensive investigation on a silty sand, which was a natural subgrade material from a road construction. The investigations included the soil properties, i.e. grading, Soil-water Characteristic Curve (SWCC) and advanced experimental testing of triaxial shearing on the saturated and unsaturated conditions. The influence of matric suction on the strength behaviour may be interpreted in related to unsaturated soil structures. The prediction of unsaturated strength can be implemented by combining the saturated soil strength with SWCC curve for practical engineering purpose. The understanding of the strength behaviour of unsaturated soil can provide reference for the engineering design in considering significant strength loss due to matric suction decrease.

Keywords: matric suction, air-entry-value, degree of saturation, shear strength

1 INTRODUCTION

A number of shallow-depth slope failures have taken place during or after rainfall in Victoria area experiencing high seasonal rainfalls and long-term infiltration of melting snow. It has been widely recognised that water infiltration has a dominant effect on the slope instability caused not only by an increase of pore water pressure in soil due to the rise of ground water level, but also by the degradation of soil strength due to reduction of matric suction. Therefore, rainfall infiltration becomes an interesting subject due to the necessity of understanding its effects on the increase of the pore water pressure and the generation of deformation in unsaturated slopes. Due to their nature as unsaturated geo-materials, it is desirable to study their behaviour using the framework of unsaturated soil mechanics.

In order to predict the stability of slopes induced by rainfalls, it is important to investigate the change of the shear strength of soils due to the water infiltration causing the reduction of matric suction. The matric suction has been found to be absolutely crucial to the stability of unsaturated slopes (Fredlund and Rahardjo 1993).

Because rigorous laboratory tests on unsaturated soil were difficult, time-consuming and, therefore, costly, estimating unsaturated soil properties from inter-phase relationships using the soil-water characteristic curve (SWCC) is very attractive to engineering practitioners. SWCC has been used as a tool either directly or indirectly in the prediction of the shear strength along with the saturated shear strength parameters (Fredlund et al. 1996; Khalili and Khabbaz 1998).

In this study, SWCC of a silty sand was measured within the matric suction up to 300 kPa and compared with best-fit estimation for engineering practice reference. The effect of matric suction on shear strength of soil will be studied by experimental work, interpreted from structure development due to matric suction and compared with different predictions. The shear strength under different matric suction was compared with the prediction from different approaches including estimation from SWCC and effective stress concept to assess the best estimations for engineering practice.

2 TESTED SOIL

The tested soil was a well-graded silty sand. The sand content was 73.5% and the fines content (predominantly silt) was 26.5%. The particle size distribution of the tested soil is listed in Table 1.

Table 1: Particle size distribution of tested soil

Sand	Silt	D10(mm)	D30(mm)	D60(mm)	c_u
73.5%	26.5%	0.007	0.12	0.26	38.46

3 SOIL-WATER CHARACTERISTIC CURVE (SWCC)

The SWCC for the tested soil was reported by Hu (2010) with matric suction up to 300 kPa. A combination of directly imposing negative pore-water pressure for matric suction less than 60 kPa and axis-translation techniques as matric suction beyond 60 kPa was used to obtain the SWCC. The result has been presented in Figure 1. An estimated air-entry-value (AEV) from the SWCC is in the range of 21 to 30 kPa. A residual matric suction of 600 kPa may be applicable for the tested soil.

Due to high variability and complexity of soil make direct determination of the SWCC costly, time-consuming and subject to significant sources of error. Many attempts have been made to derive SWCC from particle-size distribution data. These efforts include studies by Gupta and Larson (1979), Arya and Paris (1981), Fredlund and Xing (1994).

The equation proposed by Fredlund and Xing (1994) was found to best fit the data for sand soils, while van Genuchten's equation (1980) was found to be best fit to the experimental data for silt and clay (Zapata C.E. et al. 2000). However, the predictions for fine-grained soils remain rather unreliable.

Fredlund and Xing (1994) proposed the following equation to represent the SWCC.

$$\theta = C(\psi) \frac{\theta_s}{\left\{ \ln \left[e + \left(\frac{\psi}{a} \right)^n \right] \right\}^m} \quad (1)$$

Where θ is the volumetric water content; θ_s is the volumetric water content at saturation; a , n and m are fitting parameters; ψ is the matric suction; and $C(\psi)$ is correction factor defined as

$$C(\psi) = 1 - \frac{\ln(1 + \frac{\psi}{\psi_r})}{\ln(1 + \frac{1000000}{\psi_r})} \quad (2)$$

Where ψ_r is the suction corresponding to the residual water content θ_r . The fitting parameter, a , is the matric suction at the inflection point as defined by Fredlund and Xing (1994) and closely related to the air-entry value of the soil. Above equations have been often used because of its practical applicability. (Leong and Rahardjo 1997; Sillers and Fredlund 2001).

For the tested soil:

$$a = 45 \quad n = 1.48 \quad m = 0.82$$

The estimated SWCC are presented in Figure 1. The estimation matches with experimental results very well within transition zone (between AEV and residual zone).

4 SHEAR STRENGTH MEASUREMENT

4.1 Experimental Setup

A custom made triaxial apparatus was developed to test unsaturated soil strength. A radial caliper was mounted on an unsaturated specimen (85mm in diameter and 100mm in height) to monitor the diameter change with free-ends to improve the uniform deformation of specimen during shearing. Two internal LVDTs were mounted across the platens to measure vertical deformation. The vertical loading applied on soil specimen is controlled by a GDS force actuator. A 10kN internal load cell was used to measure the axial loading of the specimen.

The axis translation technique (Hilf, 1956) was used to measure and control the matric suction. The platens were fitted with under-sized high air entry (HAE) of 5Bar ceramic discs. More detail about the setup of the system was discussed in previous paper (Hu et al. 2007).

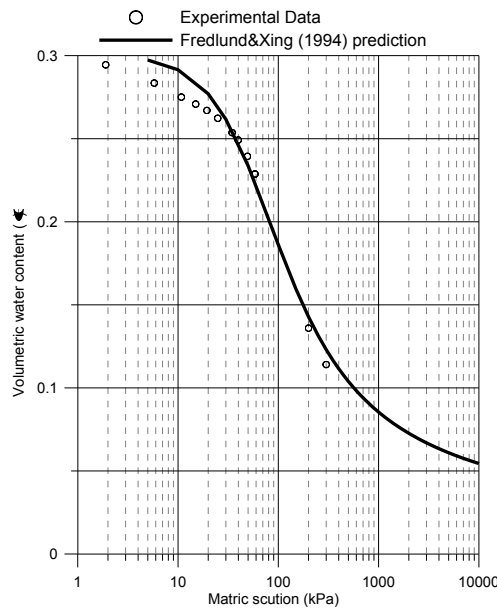


Figure 1. Measured SWCC and prediction for silty sand

4.2 Triaxial Test Results

The drained shearing tests were done on the saturated soil with the effective confining pressure ranging from 100 to 400 kPa. Its stress-strain behaviour would be taken as a benchmark for unsaturated soil. The shear strength parameters of the saturated tests are $c' = 0$, $\phi' = 34.7^\circ$.

The drained triaxial shearing tests were conducted on unsaturated soil under constant matric suction from 50 to 400 kPa, with $\sigma_3 - u_a = 100$ kPa. The stress-strain curves of the triaxial shearing test are shown in Figure 2. It is obvious that the unsaturated soil has higher peak strength than that of saturated soil. Soil behaves strain-softening when soil starts to desaturate, while strain-hardening behaviour is found under saturation ($s=0$). The higher the matric suction is, the stiffer the soil behaves and the smaller the axial strain at which deviator stress reaches its peak.

A dramatic increase of peak deviator stress was detected with matric suction from saturated to $u_a - u_w = 50$ kPa. This is due to the significant contribution of matric suction with desaturation ($u_a - u_w > AEV$). However, less increase of shear strength can be detected with the increase of matric suction as $u_a - u_w > 50$ kPa. Significant strength loss can be expected when soil becomes saturated due to matric suction decrease caused by water infiltration.

Soil structure and behavioural changes are controlled primarily by the changes in the pore-size distribution (PSD) (Kodikara et al. 1999). The pores inside the unsaturated soil are classified into two levels: micropore and macropore. The size of the two dominant pores may be associated with the two basic structural levels: (i) the macrostructure, consisting of the ensemble of aggregates with macropores between them, and (ii) the microstructure inside the aggregates. The significantly higher strength of unsaturated soil can be interpreted with its two-level structure. Unsaturated soil behaves in a more granular way than would be justified by its grading. The major mechanism involved in structure development during desaturating is the growth and aggregation of soil particles to form a stiffer structure. Particles aggregation is driven by soil suction that develops as water is removed from the soil pores during drying.

It can be seen from the test results that the contribution of matric suction to peak strength is more significant than that to post-failure shear strength. The initial fabric of two level structures of unsaturated soil including macrostructure (aggregate and inter-aggregate macro-pore) due to bonding effect of matric suction can be progressively damaged during shearing. The explanation for this could be that the contribution of matric suction to strength starts to decrease because of the breakage of aggregated units with micropores. The higher the peak strength, the faster the deviator stress drops after the peak. It may be concerned that for any designs based on peak strength less contribution of matric suction should be considered. Also the breakage will result in less volume dilatancy developed with the axial strain, which means dilatancy factor will reach the maximum. The volume behaviour and shear-dilatancy behaviour of unsaturated silty sand has been discussed in separate paper (Hu et al. 2007).

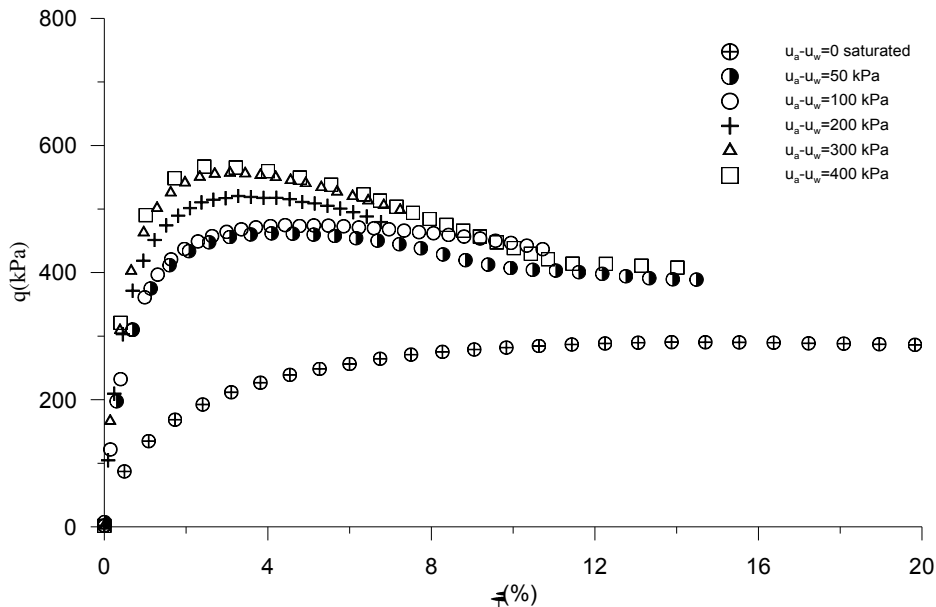


Figure 2. Stress-strain relationship of saturated and unsaturated triaxial shearing

4.3 Peak Strength Prediction

Based on experimental results, the contribution of matric suction to the strength of unsaturated soil gradually reaches a maximum limit with the increases in matric suction (Escario and Saez 1986; Gan and Gredlund 1996; Vanapalli et al. 1996; Futai and Almeida 2005).

4.3.1 Fredlund et al. (1996) Model

Soil behaviour was expressed as a direct function of two independent stress components, applied stress and matric suction, rather than in terms of a single effective stress.

$$\tau_f = c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \quad (3)$$

Where ϕ^b can be calculated by $\phi^b = \Theta^\kappa \tan \phi'$.

Garven and Vanapalli (2006) proposed the following equation to count the influence of soil plasticity index and soils structure on the fitting parameter, κ

$$\kappa = -0.0016I_p^2 + 0.0975I_p + 1 \quad (4)$$

where Θ is the normalised volumetric water content (θ/θ_s), θ is the volumetric water content, and θ_s is the volumetric water content at saturation, I_p is plasticity index. For the tested soil, sand with low plasticity fine contents, $\kappa=1.2$ was used for strength prediction.

The net normal stress, i.e. $(\sigma - u_a)$, and matric suction, i.e. $(u_a - u_w)$, are considered to make independent contribution to the shear strength of unsaturated soil. However, the interaction between them is still not clear. Some experimental evidence showed that the net stress may affect matric suction and shear strength (Escario and Saez 1986; Vanapalli et al. 1999; Rassam and Williams 1999; Ng and Pang 2000).

4.3.2 Khalili and Khabbaz (1998) Model

An exponential function was used to present the relationship between equivalent effective stress parameter χ and the suction ratio. An equivalent effective stress is defined in the following equation (Khalili and Khabbaz 1998):

$$\sigma^* = (\sigma - u_a) + \chi \left(\frac{u_a - u_w}{AEV} \right)^r \quad (5)$$

Where

$$\chi = \left[\frac{(u_a - u_w)}{AEV} \right]^{-0.55} \quad \text{as } (u_a - u_w) > AEV$$

$$\chi = 1 \quad \text{as } (u_a - u_w) \leq AEV$$

Current study involves a wide range of matric suction between 50 and 400 kPa.

$$\tau_f = c' + \sigma^* \tan \phi' \quad (6)$$

Before air enters the largest pores in the soil, the soil is still considered to be saturated. Once the differential pressure between the pore-air and pore-water pressures is larger than the AEV, air will start to enter the soil pores and the soil will start to desaturate. A linear relationship was proposed by Rassam and Williams (1999) to account for the effect that normal stress has on the matric suction contribution to shear strength.

$$AEV = AEV_0 + AEV_s (\sigma_n - u_a) \quad (7)$$

AEV_0 is Air-entry-value under zero net normal stress, which can be obtained from SWCC. AEV_s is the slope of relationship of AEV and normal stress, in the range of 0.1 and 0.6 as suggested by Rassam and Williams (1999). $AEV_s = 0.24$ is used for the tested soil. As $\sigma_3 - u_a = 100 \text{ kPa}$, $AEV = 45 \text{ kPa}$ was estimated for the strength prediction. The prediction results are presented in Figure 3.

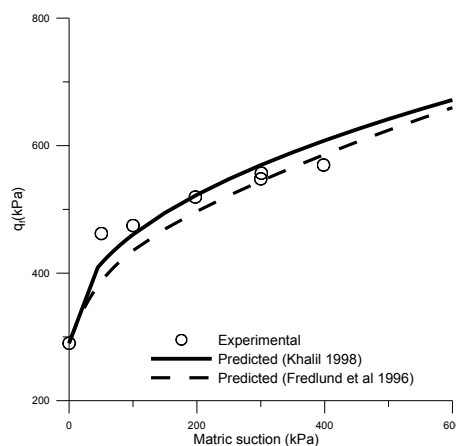


Figure 3. Shear strength prediction for silty sand

The predicted and measured shear strengths for the silty sand match very well within the tested matric suction range. As a minimum of one parameters, i.e. AEV was required for Khalili's model. It was considered significantly simple for engineer practices, especially for silty sand soils. The AEV may be measured with very simple laboratory set up to obtain this important parameter, due to its low value less than 100 kPa for sand soils. However, the saturated strength parameters, including effective cohesion and internal friction will be essential for the prediction of shear strength for unsaturated soil.

To correlate the moisture content with matric suction, SWCC with the low matric suction range will be virtually important in the estimation.

5 CONCLUSION

Sand soil presents much higher peak strength for unsaturated soil, and less increase with matric suction as it is large than AEV. Significant loss of strength due to saturation is expected as matric suction approaches AEV. The contribution of matric suction to post-failure strength is less significant than to the peak strength. Both Fredlund and Khalili models are used to predict peak shear strength in related to matric suction change. SWCC can provide significant reference for shear strength prediction to a reasonable extend for Fredlund model. The Fredlund model provides slightly under-estimated prediction by using estimated/measured SWCC within transition zone. With a simple function and single soil parameter of AEV required, Khalili's model performances slightly better and can be more easily used in engineering practices.

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