Relationship between the Soil-Water Characteristic Curve and the Unsaturated Shear Strength of a Sandy High Plasticity Clay

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Abstract

The unsaturated shear strength is an important soil property used to evaluate the performance of shallow foundation on area with fluctuating ground water table such as Sakonakhon province, Thailand. Several methods have been proposed to predict the function between the shear strength, suction and degree of saturation. In this study, the soil-water characteristic curve has been used as an effective tool in the prediction of the shear strength along with the saturated shear strength parameters of a high plasticity sandy clay from Sakhonakhon province, Thailand. A series of samples were prepared at various degrees of saturation for constant-water content direct shear tests and the soil-water retention curves for the soils were determined using miniature KU-tensiometer in low suction range (0-90 kPa) and psychrometer at higher suctions (1,000-1,000,000 kPa). The result shows that the SWCC can be satisfactorily fitted with van Genuchen's model and the effective cohesion increases non-linearly with suction. A general form for shear strength equation based on Vanapalli (1996) model and soil-water characteristic curve of unsaturated Sakhonakhon clay is also developed in this study.

1. Introduction

Shear strength is an important property used for designing various geotechnical works. Usually in the engineering practices, analyses in soil mechanics are done with assumption of fully saturated soil although soils often encountered with partially saturated condition, especially for problems near surface such as shallow foundation in North-Eastern part of Thailand. This is a reasonable assumption though, considering the worst case condition of soil shear strength encountered during full saturation.

Nevertheless, to understand the actual behavior of unsaturated soil especially the bearing capacity of shallow foundation in-situ, a number of researchers have developed theories for such soils, e.g. [1], [2], [3], [4]. To obtain the shear strength parameters of an unsaturated soil requires an extension of conventional laboratory facilities such as triaxial apparatus or direct shear box with axis-translation or osmotic system, which are costly, and thus is considered as limitation for research.

This paper investigates the relationship between the soil-water retention curves and the shear strength at difference moisture contents for a sandy high-plasticity clay from Kasetsart University Chalermprakiat Sakhonakhon province campus, where cracking in 4-storey or lower buildings are encountered. The cause of cracks in buildings has also been investigated by Nokkaew and Nontananandh (2008) and believed to be related to changes in soil properties due to change in moisture conditions. A number of undisturbed samples, collected using KU- miniature thin-wall sampler, developed by Kasetsart University, and block sampling in a test pit, were prepared for consolidated direct shear tests and soil water characteristic curves. A general form for shear strength equation based on soil-water characteristic curve of unsaturated Sakhonakhon clay is also proposed using the model of Vanapalli (1996), and used for prediction of bearing capacity of shallow foundations in the campus.

2. Background

2.1 Soil water characteristic curve (SWCC) equation.

Soil water characteristic curve is the relationship between volumetric water content ($\theta = \frac{V_w}{V_T}$) and soil suction, $s = u_a - u_w$ (equal to negative pore water pressure at atmospheric condition). A number of equations for SWCC have been proposed in the literature (e.g. [6], [7],[8], [9]). The van Genuchten expression is widely used due to its having only a few parameters with clear physical meanings and simplicity, e.g. [6]. The equation is;

$$\Theta, S_e = \left[\frac{1}{1+(a\psi)^n}\right]^m \tag{1}$$

where Θ, S_e = effective degree of saturation = $(S - S_r)/(1 - S_r)$, S_r= Residual Saturation, ψ = soil suction (unit in kPa in this paper), a, m and n= fitting parameters.

This relationship of SWCC is one of the most important parameter in unsaturated soils, adopted by geotechnical engineers for the prediction of various properties including shear strength, permeability, and thermal coefficient [10]

2.2 Unsaturated soil strength equations

Fredlund et al. (1978) introduced an additional variable ϕ^b to capture the increase in shear strength with increasing matric suction, and proposed the unsaturated shear strength equation in term of two stress state variable; net normal stress $(\sigma_n - u_a)$ and matric suction $(u_a - u_w)$ The equation is;

$$\tau_f = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \tag{2}$$

Where, ϕ_b = internal friction angle associated with matric suction.

Vanapalli et al. (1996) proposed a non-linear function for predicting the unsaturated shear strength using soil water retention curve and saturated shear strength parameter. The equation is;

$$\tau_f = c' + (\sigma_n - u_a)\tan\phi' + \Theta^{\kappa}(u_a - u_w)\tan\phi' \tag{3}$$

Where κ = fitting parameter used to obtain a best fit between the measured, predicted values and ϕ'= drained friction angle

3. Materials

All specimens are undisturbed sample obtained from Kasetsart University Chalemprakiat Sakhonnakhon Province Campus, Thailand at depth of 2.0-2.5 m, at which shallow footings in the campus are normally founded. The liquid limit, w_L, and the plastic limit, w_p are 54% and 20%, respectively. The specific gravity, G_s is 2.74 and the natural gravimetric water content, w_n is 33% for soil samples collected toward the end of rainy season. The percentage of sand-, silt- and clay-size particles are 21%, 28% and 51%, respectively. The soil is classified as sandy high plasticity clay.

4. Soil-water characteristics curve

In this study, the two undisturbed samples were prepared for testing of soil-water characteristic curves at geotechnical engineering laboratory, Kasetsart University both at Bangkok and Sakhonakhon campuses. For low suction, the soil suction were measured by KU tensiometer, developed by Jotisankasa et al. [11], consisting of three parts; MEMs pressure sensor, a transparent acrylic tube and a porous ceramic disc. The tensiometers are calibrated using hanging water column, for suction range 0 to 90 kPa. For higher suctions, in the range of 1,000- 1,000,000 kPa, a psychrometer, based on a capacitive relative humidity sensor and thermister is used for total suction measurement [12].

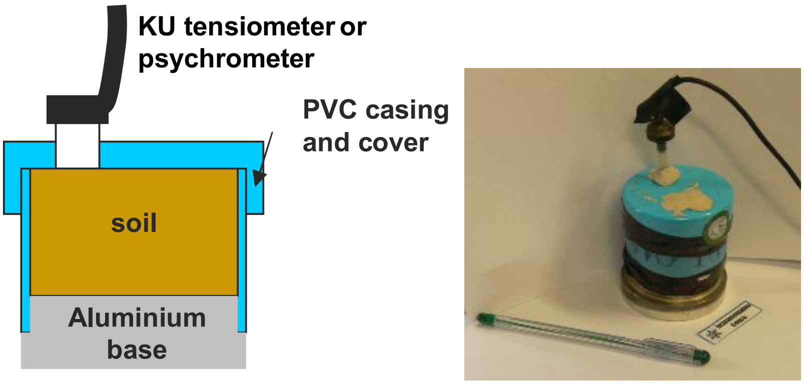

Figure 1: photo showing soil suction measurement by KU tensiometer and psychrometer for soil water characteristic curve determination

Figure 2a) shows the relationship between soil suction and volumetric moisture content of two representative samples. The air entry suction of the soil is in the range of about 20 to 100 kPa. The test procedure involved gradually wetting specimen from initial moisture content condition by fog generator up to the suction of about 1 kPa, then soaking the sample for 4 days, before gradually air-drying the sample incrementally while measuring the suctions and soil weight at every stage of wetting and drying. Figure 2b) depicts the volume change of samples from saturation to air-dried state. Most volume change takes place when suction increases from 100 to 10,000 kPa, with the volumetric strains being 7.78% and 11.50% for samples 1 and 2, respectively.

Figure 3) presents the SWCC of Sakhonakhon sandy clay plotted as a degree of saturation versus soil suction and the fitting curve using the mathematical equation proposed by van Genuchten(VG) model (1980). The model parameters used in equation 1 are; a= 0.00018, n = 1.9, m = 0.47; the correlation was of R^2 equal 0.97 for sample 1, 0.96 for sample 2 and the SWCC equation by van Genuchen model is;

$$S_e = \left[\frac{1}{1 + (0.00018\psi)^{1.9}} \right]^{0.47} \tag{4}$$

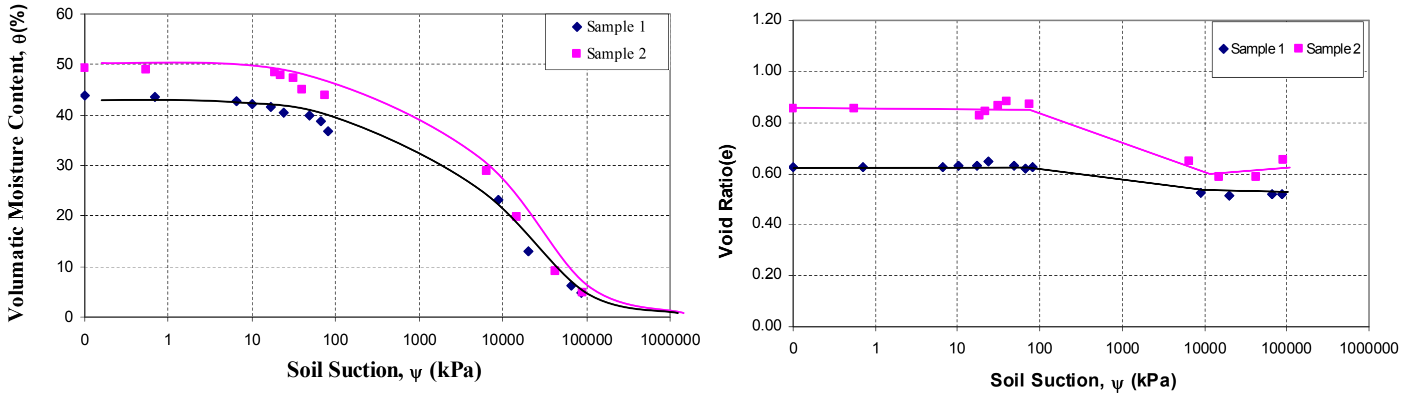

Figure 2: Soil-Water characteristic curves for high plasticity sandy clay samples 2a) relationship between soil suction and volumetric moisture content 2b) relationship between soil suction and void ratio

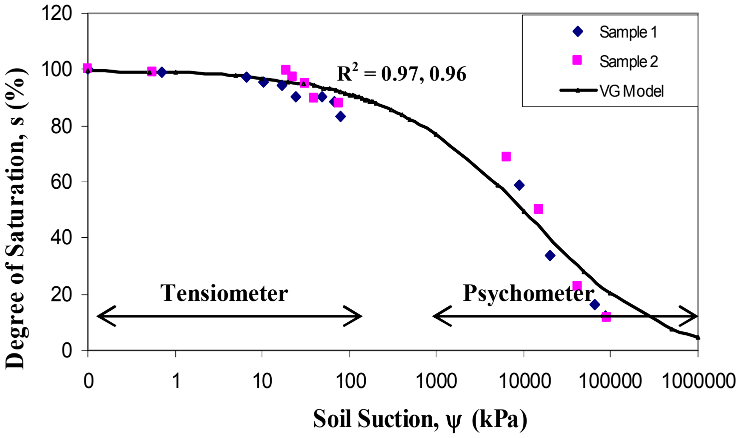

Figure 3: Relationship between soil suction and degree of saturation

5. Shear strength-suction- normal stress relationship

A series of consolidated drained shear tests were performed on fully saturated samples. In addition, consolidated constant water content tests were also carried out on unsaturated samples. The result shows that most stress-strain relationships for the soils appear to be strain-hardening for both soaked and unsoaked samples. Figure 4 shows relations of failure envelope with respect to normal stress obtained from direct shear tests of the soil at initial degree of saturations 76 %, 88% and 99 % as summarized in Table 1. The consolidated drained shear strength of the soil is also depicted and is summarized in table 1. The effective strength parameters are obtained from drained tests with c' = 17.35 kPa and ϕ' = 22.54°.

Table 1: Summary of effective shear strength parameters of the studied material

Degree of Saturation	76%	88%	99%	Drained test (soaked sample)
	Unsoaked sample			
c, kPa	32.72	32.5	12.53	17.35
ϕ, degree	27.39	20.42	25.03	22.54

After obtaining effective shear strength parameter, unsaturated shear strength of the soil can be expressed by Equation (5). The additional shear strength due to suction is called “ apparent cohesion(c^s)” . Lu and Likos(2004) described the “apparent cohesion” arise from interparticle physicochemical forces such as van der waals attraction and sometimes can be called “capillary cohesion”[13]. Figure 5 shows the value of apparent cohesion (c^s), derived from ultimate shear strength at different degree of saturations based on equation 5, with assumption of residual saturation (S_r) being zero, and effective degree of saturation equal degree of saturations ($\Theta \approx S_e$). A general form for shear strength equation using soil-water characteristic curve of unsaturated sandy clay is also presented in this figure by the model of Vanapalli (1996) with κ = 12 and R^2 = 0.903.

$$\tau = c' + \sigma \tan\phi' + c^s \tag{5}$$

When

$$c^s = \Theta^\kappa (u_a - u_w) \tan\phi' \tag{6}$$

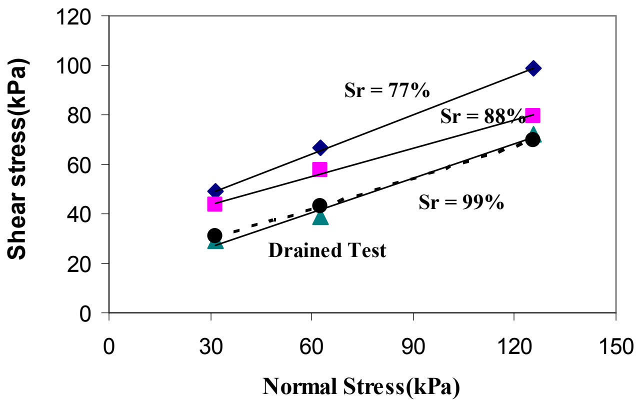

Figure 4: Relationship between normal stress and shear Strength at different moisture contents

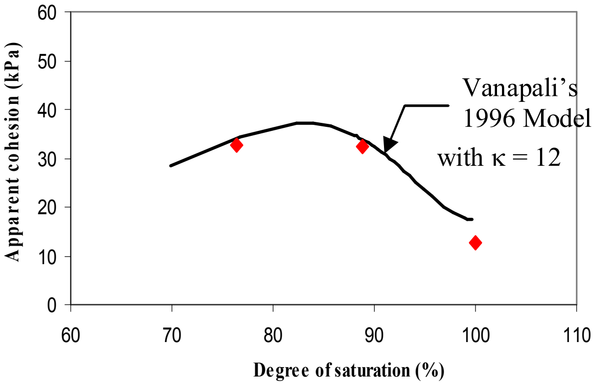

Figure 5: Relationship between degrees of saturation and apparent cohesion of plasticity sandy clay

6. An application of unsaturated shear strength for bearing capacity

The bearing capacity of unsaturated soil can be estimated by addition of the capillary cohesion in any bearing capacity equation from classical soil mechanics [3]. Figure 5 shows the degree of saturation versus bearing capacity calculated by Terzaghi bearing capacity equation for a representative shallow square footing (3.5 m x 3.5 m) of a building in the campus which has cracking due to differential settlement. The results are summarized in table 2 and shows that bearing capacity could be halved when degree of saturation increase from 86% to 100%. To investigate the actual cause of differential settlement, more detailed stress-strain behavior of the sandy clay should be studied further. Yet, the findings from this preliminary study indicate that the cracking problems are likely to be involved with changes in soil moisture condition underneath the foundation.

Table 2: Summary of effective shear strength parameters of the studied material

Degree of Saturation(%)	82	86	90	93	96	100
Ultimate Bearing Capacity,qc(kPa)	940	925	833	704	575	459
Percentage of increasing qc(%)	205	201	181	153	125	100

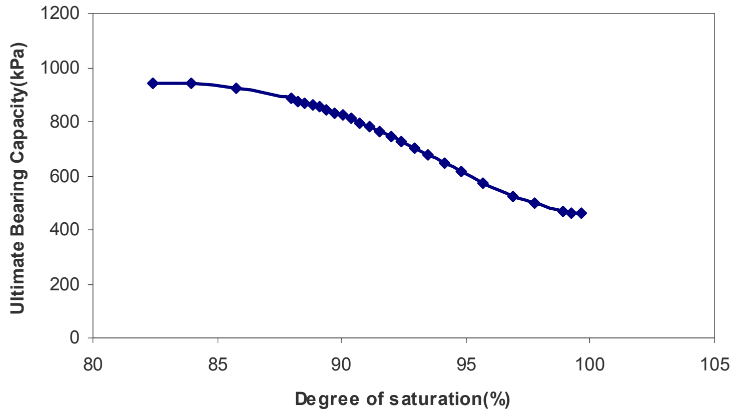

Figure 5: Degree of saturation versus bearing capacity of shallow foundation constructed on the problem soil

7. Conclusions

To understand the actual behavior of unsaturated soil beneath shallow footings in Sakhonakon campus of Kasetsart University, a series of direct shear tests and soil water characteristic curve tests have been performed on undisturbed sandy clay samples at different degree of saturation. The results of soil water characteristic curves are well fitted with van Genuchen(1980) model. The cohesion due to suction can be predicted using the Vanapalli 1996 model with $\kappa = 12$. Based on the simple Terzaghi bearing capacity equation with the measured capillary cohesion, the bearing capacity is shown to reduce to half a value when degree of saturation increases from 86% to 100%. Therefore, the soil moisture condition underneath the foundation is very important in controlling the performance of shallow foundation in the campus.

8. References

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