Shear Strength Behavior of an Unsaturated Clayey Soil

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Abstract. Recently the study of shear strength of unsaturated soil is gaining more interest in research and practice. In this study the triaxial shear test and filter paper method were undertaken to study the shear strength behavior of unsaturated soil. The Clayey soil from central India was tested to understand the unsaturated shear strength behavior. The shear strength behavior was analyzed by plotting relationship between shear strength (τ) versus matric suction ($u_a - u_w$). The failure envelope resulting from relationship between the shear strength and matric suction shows nonlinear behavior and provides the shear strength parameter with respect to suction ($Ø^b$). In this experimental program, the shear strength behavior of unsaturated soil is studied using the soil water characteristic curve (SWCC) and the nonlinearity between shear strength and the matric suction is observed. The nonlinearity is mainly due to desaturation of soil which starts from air entry value and continued till residual suction value and is affirmed and supported by the experimental results obtained in this study.

Keywords: Unsaturated soil, Shear strength, Suction, SWCC

1 Introduction

The shear strength of unsaturated soil appeals more research in the geotechnical engineering and practice from last few decades. The shear strength of unsaturated soil governs main parameters of geotechnical engineering such as bearing capacity, earth pressure, slope stability etc. In India, engineers are mostly come across with the unsaturated clayey soils. The shear strength of unsaturated clayey soil is strongly influenced by the physico-chemical interaction between water and clay minerals. Therefore, it is necessary to study the shear strength behavior of unsaturated clayey soil [17].

The thought process to study shear strength behavior of unsaturated clayey soils started from last five decades. Numerous experimental programs were conducted by various researchers to understand the shear strength behavior of unsaturated soils from different countries. A series of consolidated drained tests were performed with modified triaxial cell using axis translation technique to study the shear strength behavior of unsaturated Dhanauri clay and Madrid gray clay [14]. The series of six undrained and unconfined compression tests were conducted on unsaturated compacted clayey soil comprising 52% sand, 18% silt and 30% clay [6]. Guadalix Red silty clay was investigated by performing the test under a net normal stress of 120 to 600 kPa for suction lower than the air entry value and obtained elliptical failure envelope [8]. The effect of suction on shear strength was studied by testing the clayey soil from Ningxia Hui, China with advanced triaxial test apparatus [16]. The suction-controlled direct shear test was performed on unsaturated expansive clay and studied the stiffness of clay with suction [16]. The consolidated drained test with modified direct shear apparatus was performed for investigating the Regina clay and Glacial till (clayey till) respectively [10] [15]. Most of the investigators studied the shear strength behavior on various types of unsaturated soils and observed the non-linear behavior of strength envelope. But very few researchers studied the shear strength behavior of unsaturated clayey soil in Indian context.

Therefore, clayey soil from central India was investigated to study the shear strength behavior in this research work. The conventional triaxial shear test and filter paper method were performed for shear strength and suction measurement respectively. The soil water characteristic curve was also developed from the data obtained from experimental work. The shear strength was interpreted for range of 60 kPa and 275 kPa matric suction.

Unsaturated soil property functions can be used positively with reasonable accuracy by performing an indirect laboratory test such as a pressure plate test or filter paper method to develop the soil water characteristic curve in research work. The filter paper is the only suction measuring method which measures the whole range of interest [12]. The failure envelope for an unsaturated soil was appeared to be nonlinear with respect to the matric suction axis.

2 Unsaturated shear strength

The concept of unsaturated shear strength was begin with the general theory of consolidation for an unsaturated soil [4]. Initially the influence of suction on compacted cohesive soils was studied [11]. The Mohr- Coulomb strength relationship was proposed in the form of Equation 1 to describe the shear strengths of unsaturated soils:

$$\tau_f = C + \sigma \tan Ø \qquad (1)$$

Where,
τ_f= shear strength
C = cohesion
σ = Normal stress
Ø = Angle of shearing resistance

The two independent stress state variables such as the net normal stress ($\sigma - u_a$) and the matric suction ($u_a - u_w$) were recommended [7], instead of a single effective stress variable for interpreting stress-strain behavior of unsaturated soils. Later, the unsaturated shear strength equation comprising two independent stress state variables were proposed [9]. The net normal stress (σ-u_a) and the matric suction (u_a-u_w) are the two most commonly used stress state variables for expressing the unsaturated shear strength equation in the following form:

$$\tau_f = c' + (\sigma - u_a)\tan Ø' + (u_a - u_w)\tan Ø^b \quad (2)$$

Where,
τ_f= shear strength,
c' = Effective cohesion,
Ø' =Effective angle of shearing resistance,
$Ø^b$ – Shearing resistance with respect to matric suction.
$(\sigma - u_a)$ = Net normal stresses
$(u_a - u_w)$ = Matric suction

$Ø^b$ indicates the rate of increase in shear strength with respect to matric suction. From experimental and theoretical studies, it is stated that $Ø^b$ is the nonlinearly decreasing function of matric suction. The modified Mohr-Columb's failure envelope is observed between the shear stress (τ) and matric suction (u_a-u_w) and the $Ø^b$ can also be defined as an angle of internal friction with respect to (u_a-u_w) variation under a constant (σ - u_a).

Vanapalli (1996) elaborated detail procedure for interpreting confined compression test results and derived the Equation 3 for angle of friction with respect to suction. This equation was exclusively suggested for the confined undrained triaxial test [15].

$$\tan Ø^b = \frac{[q_u(\cos Ø' + \sin Ø' \tan Ø')]}{(u_a - u_w)} - \frac{[(c_u + \sigma_3)\tan Ø' - c']}{(u_a - u_w)} \quad (3)$$

Where, q_u= Failure deviator stress from the undrained triaxial test
c_u = Undrained cohesion

3 Material and Methodology

Triaxial shear test was selected to evaluate the shear strength clayey soil samples owing to its pervasiveness. The filter paper was used for measuring suction values in the range of 0-350 kPa. The suction values were obtained from the calibration curves developed in this study.

The highly plastic clayey soil available in central India was investigated in this research work. Primarily index properties were assessed to classify the soil. Results obtained from Practical size distribution, Liquid limit, Plastic Limit and Specific gravity are summarized in Table 1.

Table 1. Index Properties

Properties	Values
Gravel	0
Sand	9.47%
Silt	47.23%
Clay	43.30%
Liquid limit	68.60%
Plastic Limit	29.10 %
Plasticity index	35.50%
Specific gravity	2.61

The soil was categorized as clay of high plasticity on the basis of results obtained from the various laboratory test conducted (Table 1). Furthermore, standard proctor test was performed to obtain the maximum dry density (14.4 KN/m^3) and optimum moisture content (25%) respectively.

The soil specimens were compacted with different water content and maintained the various optimum conditions i.e. dry of optimum, optimum, wet of optimum. The series of tests were performed on identical clayey soil samples. The same process was followed for preparation of soil samples for performing triaxial shear test and filter paper method. The soil sieved through 2 mm sieve mixed with the required quantity of distilled water and it was placed for 24 hours to establish the hydraulic equilibrium. After achieving the equilibrium soil was compacted.

The compacted soil was then left for another one day (48 hours) to achieve the equilibrium. The soil samples were extracted from the compacted soil for traixial as well as filter paper test. The soil sample of size 38 mm diameter and 76 mm height was extracted for the triaxial test [1]. Similarly, the soil sample of size 50 mm diameter and 70 mm height was extracted for the filter paper method [2]. Fig. 1 shows the molds used for extracting the samples for triaxial and filters paper method. After sampling the samples were kept in a plastic bag which was labeled by the sample number and stored in the desiccator (see Fig. 2) for 24 to 48 hours equilibration period until being tested. Density of each set was confirmed before commencing the triaxial and filter paper method.

Fig. 1. Molds and Samplers

Fig. 2. Soil samples in desiccator

3.1 Triaxial Test

The compacted soil samples obtained with different initial water content and different dry densities were tested under undrained condition. Three soil samples from one set were tested with three different confining pressures, i.e. 50 kPa, 100 kPa, 150 kPa. Confined compression triaxial shear tests were conducted on specimens with the same initial conditions. The specimens were sheared immediately after the application of the confining pressure at a constant strain rate. The confining pressures applied were in the range of 50 to 100 kPa. The tests were performed on soil samples at various optimum conditions i.e. dry of optimum, optimum, wet of optimum.

The effective shear strength parameters: cohesion (c') and angle of shearing resistance (Ø'), were obtained from the consolidated drained test. The series of consolidated drained test was performed on the soil samples compacted at Optimum moisture content and maximum dry density. Three samples were consolidated under pressure of 50 kPa, 100 kPa and 150 kPa for twenty-four hours. Samples were tested under confining pressure of 50, 100 and 150 kPa. Consolidated samples were sheared at the rate of 0.0125 mm/min, which enabled drainage during the testing, as the sample was made of clayey soil [3].

3.2 Filter paper method

The combination of procedure suggested in [1] and [5] was implemented to accomplish filter paper method. Suction was obtained from the calibration curve after attaining equilibrium between the soil and filter paper. The ash free and quantitative type II i.e. Whatman No. 42 filter paper having a diameter 5.5 cm was used as per ASTM D5298 guidelines. The objective of the calibration of the filter paper for total suction was to place the filter paper above the salt solution in such a way that transfer of water to the filter paper takes place only by vapor absorption. The water content of filter paper at equilibrium stage and calibration equation gives the suction of soil. Both the non-contact and contact filter paper methods were used to quantify the total and matric suctions respectively.

4 Results and discussion

4.1 Soil water characteristic curve

The relationship between shear strength of unsaturated soil and soil water characteristic curve is presented in Fig 3. The soil water characteristic curve usually developed with the help of pressure plate method. However, it was develop using data obtained from filter paper method in this study. The use of the filter-paper method is adequate to construct soil water characteristic curve (see Fig. 3) for clayey soil of central India. The matric suction ($u_a - u_w$) is ranging from 60 kPa to 300 kPa.

The results were studied by categorizing the compacted soil into three different initial conditions, wet of optimum, optimum and dry of optimum. Suction was measured as soil de-saturate from the saturated to dry state as compacted soil. Suction increases slowly as water content decreases in wet of optimum condition. And in case of optimum condition, the suction values suddenly rise with decrease in water content. In dry of optimum condition suction gradually decreases again due to inadequate capillary forces in pores. Also, when a soil sample is dry, with a suction value higher than 300 kPa, it was difficult to obtain good sample. Thus, it was not possible to establish proper contact between the soil and the filter paper. It causes inaccuracies in suction results and the same has been observed by other researchers [5] [13]. Thus, the use of filter paper method restricted for developing the soil water characteristic curve within the range of 0- 300 kPa. The attempt of measuring the suction beyond 300 kPa was futile since it results scattered curves due to insufficient contact between soil and filter paper. However all the data points were included within the range of 0 to 300 kPa.

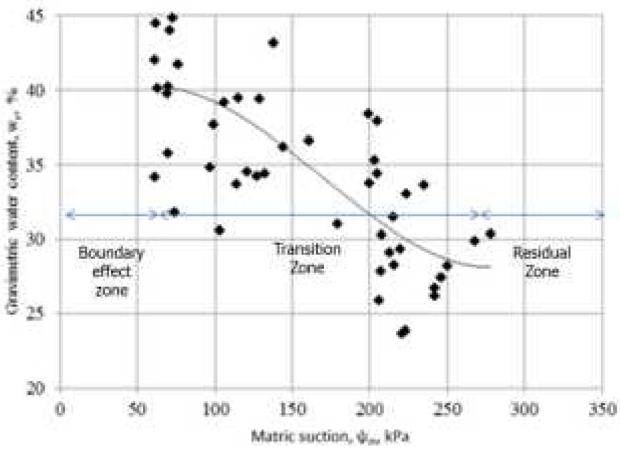

Fig. 3. SWCC (w_s Vs ψ_m) for Central India Clayey soil

4.2 Shear strength

The shear strength test and suction results obtained from the triaxial test and filter paper method respectively were analyzed by plotting relationship between shear strength (τ) versus matric suction ($u_a - u_w$). The failure envelope obtained can be used to obtain the shear strength parameter with respect to suction $Ø^b$ that shows the non-linear behavior.

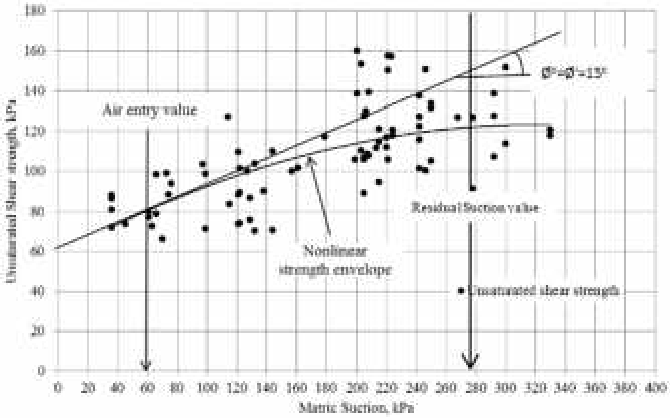

Fig. 4. Failure envelope from shear strength Vs matric suction relation

The triaxial shear test results on unsaturated clayey soil exhibits significant nonlinearity for the failure envelope with respect to the matric suction are illustrated in Fig. 4. The $Ø^b$ angle originate at a value equal to Ø' (i.e., 15^0) where the matric suction is equal to zero and decrease significantly at matric suctions in the range of 60- 300 kPa. The scatter in the failure envelopes (Figs. 4) appeared due to deviations in the initial void ratios of the soil samples. However, it is difficult to quantify the change in void ratio of the soil at failure of specimen.

The strength behavior of soil was studied with soil water characteristic curve of soil developed from the suction results. The linear increase in shear strength with respect to suction was observed up to the air-entry value i.e. 60 kPa. This value of suction corresponding to the air entry value gives the point at which air entered the largest pores of the soil. At this stage, the desaturation starts from and continues till the soil reaches the residual suction value i.e 275 kPa. In between air-entry value and residual suction value the rate of distortion was higher; and nonlinear increase in shear strength is observed. Beyond the residual suction value, the trend of curve is observed as horizontal which indicates the shear strength remains constant with increase in matric suction. During experimentation, it was observed that soil started losing its strength. The two parts of strength envelope i.e. the linear and a curvilinear segment is usually detected. The linear segment was transformed to the curvilinear segment at about the air entry value of soil.

The boundary effect zone, almost voids are filled with water i.e. soil is mostly saturated where suction is not observed. The nonlinear (curvilinear) variation in shear strength envelop was observed only in the transition zone (Fig. 4 and 5) due to desaturation process in this zone and the desaturation starts from air entry value (60 kPa). In desaturation stage suction increases speedily and it is observed that small change in water content results large change in suction. The nonlinear shear strength behavior is observed till residual suction value (275 kPa) up to which desaturation progresses. After this the residual zone started in which soil tends to dry and the effect of suction is reduced. The unsaturated shear strength parameter $Ø^b$ is equal to the effective friction angle Ø' up to air entry value; and $Ø^b$ decreases as the soil entered into the transition zone. The unsaturated shear strength at the stage of air entry value was observed as 80 kPa and 120 kPa at the residual suction value.

5 Conclusion

The shear strength of unsaturated soil derived from the combination of filter paper and conventional triaxial test was demonstrated for the clayey soil from central India. The identical unsaturated soil specimens were tested under different initial conditions i.e wet of optimum, optimum and wet of optimum to validate the feasibility of this combined method.

The shear strength behavior of unsaturated soil is studied using the soil water characteristic curve and the nonlinearity between shear strength and the matric suction is observed in the failure envelope of the clayey soil within transition zone only. The nonlinearity is mainly due to desaturation of soil which starts from air entry value and continued till residual suction value and is affirmed and supported by the experimental results obtained in this study on compacted clayey soil. The air entry value and residual suction value are identified on the desorption curve; the residual zone is hardly noticeable. It can be stated that the failure envelope appearances the nonlinearity when wide range of matric suctions (e.g., 0-500 kPa) were quantified in the investigation. More research is required to understand the properties of unsaturated soil.

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