Shear Strength Characteristics of Unsaturated Residual Soils

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ABSTRACT: The tropical climate conditions cause the residual soils near ground water level to be in an unsaturated state generally. Matric suction enhance the shear strength of the soil. In tropical countries like Sri Lanka where the soil formation is mainly residual, this added shear strength is no longer reliable due to frequent rainfall periods. With rainfall infiltration, the matric suction reduces and the shear strength diminishes making the slopes vulnerable. Therefore, it is necessary to study how the moisture content of soil is affected after the rainfall and how it can be related to shear strength. As an initial step, the variation of apparent cohesion with degree of saturation was investigated in the present study for residual soil obtained from the site of the failed slope at Southern Transport Development Project in Welipenna. Direct shear tests was preferred in the study over triaxial test because of the shorter time taken for the pore water pressure to reach equilibrium.

1 INTRODUCTION

Sri Lanka, which has a climate condition of tropical wet and dry, has residual soils that developed mainly from metamorphic rocks. Ground water table is generally low in these conditions. The soils are therefore generally unsaturated and possess negative pore water pressures. Climatic changes greatly affect the soil properties, negative pore water pressure and shear strength of unsaturated soils.

The matric suction plays a vital role in enhancing the shear strength of the soil. In tropical countries like Sri Lanka where the soil formation is mainly residual, this added shear strength is no longer reliable due to frequent rainfall periods. With rainfall infiltration, the matric suction reduces and the shear strength diminishes making the slopes vulnerable. Therefore, it is necessary to study how the moisture content of soil is affected after rainfall and how it can be related to shear strength. As an initial step, the variation of apparent cohesion with degree of saturation has been investigated in the present study for residual soil obtained from failed slope of Southern Transport Development Project (STDP) in Welipenna. This study is based on direct shear tests performed on undisturbed residual soil specimens in unsaturated state.

The results of this research will be useful for future studies on slope stability analysis. In the design of rainwater drainage systems, the results can be used to determine the apparent cohesion which must be maintained in the soil with similar history of formation as that of Welipenna. By maintaining sufficient apparent cohesion in the soil, the slope stability shall be developed internally with lower scale or absence of stabilization techniques such as retaining wall and anchors.

2 OBJECTIVES

The aim of this research is to determine the variation of unsaturated shear strength parameters of residual soil obtained from failed slope of STDP in Welipenna. To accomplish this aim, soil classification, determination of shearing rate required for 90% consolidation, determination of consolidated drained shear strength parameters and derivation of the relationship between the apparent cohesion and degree of saturation of soil were identified as main objectives.

3 SHEAR STRENGTH OF UNSATURATED SOILS

The mechanical behaviour of unsaturated soil depends on two independent stress state variables, namely the net normal stress, $(\sigma - u_a)$, and matric suction, $(u_a - u_w)$. Fredlund et al. (1993) proposed the equation 1 for interpreting the shear strength of unsaturated soils, which have planar failure surface, in terms of the two stress state variables.

$$\tau_{ff} = c' + (\sigma_f - u_a)_f \tan \phi' + (u_a - u_w)_f \tan \phi_b \quad (1)$$

where, τ_{ff} is the shear stress on the failure plane at failure, c' is the effective cohesion intercept, $(\sigma_f - u_a)_f$ is the net normal stress at failure, u_{af} is the pore air pressure at failure, ϕ' is the angle of internal friction associated with net normal stress state

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variable, $(u_a - u_w)_f$ is the matric suction on failure plane at failure, and ϕ_b is the angle indicating the rate of increase in shear strength relative to the matric suction $(u_a - u_w)_f$. The extended Mohr-Coulomb envelope defines the shear strength of an unsaturated soil. It can be either planar or curved. Unlike a curved failure envelope, planar failure envelope is assumed to have a constant slope angle, ϕ_b.

The soil-water characteristic curve which is one of the important unsaturated soil properties of residual soils, defines the relationship between the water content and matric suction in the soil. The general trend of soil- water characteristic curve is that the water content decreases as soil matric suction increases.

4 METHODOLOGY

The methodology followed in this research to accomplish the objectives is as listed below.

- Background study and clarifications about the research
- Literature review
- Acquisition of sample and preparation of sample for testing
- Performance of laboratory tests
- Analysis of results

5 EXPERIMENTAL WORKS

A series of experiments required to find out essential parameters were performed following the guidelines given on BS 1377.

Soil classification was done according to unified classification system. Basic tests such as particle size distribution and consistency limit tests were performed for the soil classification. It was required to know the time needed for 90 % consolidation of soil in order to come up with an appropriate shearing rate for sample, which ensures complete dissipation of excess pore water pressure. Consolidation test was conducted for this purpose prior to the commencement of primary tests.

In order to find out the consolidated drained shear strength parameters, series of direct shear tests were conducted on undisturbed specimens by varying the degree of saturation.

5.1 *Soil classification tests*

Residual soils possess variability in its nature. Hence, it was expected that the Welipenna soil can have range of soil particles. In particle size distribution test, wet sieving was done for coarser particles as soil was found to be cohesive and hydrometer test was conducted for finer particles as their percentage in the soil was greater than 10%. Consistency limit tests were carried out to identify the dominating type of finer particle, either silt or clay. Fig. 1 shows the particle size distribution in the soil.

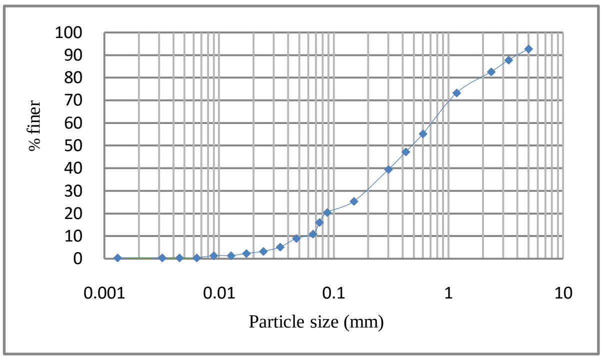

Fig. 1 Particle size distribution

The liquid limit and plastic limit of soil were 39.6% and 35.17% respectively. The plasticity index of 4.47% indicated that the soil is slightly plastic. With that, the soil was classified as SM (silty sand) according to the unified classification system.

6 DIRECT SHEAR TESTS

The direct shear test was chosen over other tests for this study because of the shorter drainage path of soil sample and thus less time taken to dissipate the excess pore water pressure. Test was carried out on undisturbed residual soil specimens in order to determine the shear strength parameters of soil in its natural state. The purpose of the direct shear tests was to find out the variation of drained shear strength parameters at different degree of saturation. The degree of saturation of test specimens was changed by adding different amount of water to natural sample. Degrees of saturation achieved were 30%, 45%, 63% and 78%. For each degree of saturation, specimens were tested under net normal stresses of 50 kPa, 100 kPa, 150 kPa and 200 kPa with a shearing rate of 0.05 mm/min. The details of the testing program for Welipenna soil are presented in Table 1.

6.1 Curve fitting

Shear stress versus normal stress relationship of soil was established mathematically. From that, the friction slope of unsaturated soil specimen associated with net normal stress variable was found to vary between 39˚ and 45˚. The slope, ϕ′ is constant for specific soil. Hence, manual curve fitting was performed for the test results by varying the slope angle between 39˚ and 40˚. The analysis expressed the friction angle of soil as 39.3˚.

In manual curve fitting, consideration was given to the variables such as dry density, moisture content and observed sample variability such as presence of large stones and local shear failure. Because the dry density of specimens showed variation, insitu density of samples was taken to be 1250 kgm^{-3} which is the average density of samples. The actual shear strength and the shear strength of soil predicted from manual curve fitting are presented on Table 2. Fig.2 shows the variation of actual and predicted shear strength. The summary of curve fitting is presented in Table 3.

Table 1. Testing program

Test number	S_r (%)	w (%)	γ_d (kg/m^3)
1	32.3	17.89	1065.0
	30.8	15.49	1125.6
	26.7	14.01	1098.9
2	43.4	21.82	1165.5
	41.7	16.78	1306.7
	52.3	19.67	1206.9
3	63.1	27.63	1216.1
	64.1	30.58	1160.3
	63.0	18.80	1463.5
	60.5	19.75	1406.8
4	77.9	34.18	1214.1
	79.0	30.91	1288.9
	77.7	27.70	1343.9
	78.1	38.83	1133.7

Table 2. Actual shear strength and predicted shear strength

S_r	Normal stress (kNm^{-2})	Actual shear strength (kNm^{-2})	Predicted shear strength (kNm^{-2})
30%	50	83.13	109.82
	150	159.75	190.07
	200	232.29	230.19
45%	50	82.36	84.62
	150	214..81	166.47
	200	192.15	207.39
63%	50	94.84	92.82
	100	155.94	130.94
	150	186.31	169.07
	200	222.42	207.19
78%	50	66.08	79.62
	100	182.00	120.54
	150	180.52	161.47
	200	241.80	202.39

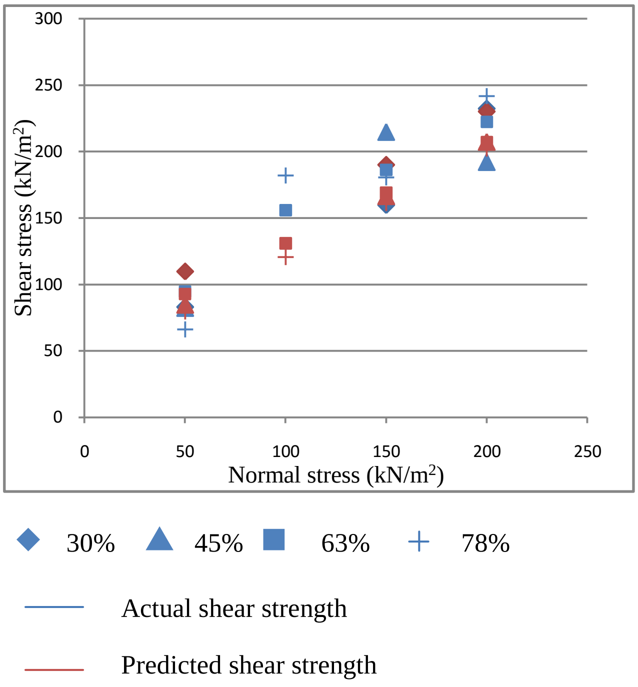

Fig. 2 Actual shear strength and predicted shear strength

The summary of curve fitting is presented on Table 3.

Table 3. Apparent cohesion of soil

Degree of saturation (%)	Apparent cohesion (kPa)
30	69.69
45	43.69
63	54.69
78	38.69

7 DISCUSSION

The results of direct shear test conducted on undisturbed residual soil samples obtained from Welipenna site have been analyzed according to shear strength theory of unsaturated soil (Fredlund and Rahardjo,1993). The results indicate that the soil has a friction angle of 39.3˚. The basic tests such as particle size distribution test and consistency limit test performed on the soil confirms such higher value by indicating that the soil is well graded and considerable percentage of finer particles present in the soil making a bond with coarser particles which eventually makes the soil slightly plastic.

The apparent cohesion of the soil can be expressed as,

$$c_a' = c' + (u_a - u_w) \tan \phi_b \quad (2)$$

The shear strength of the tested soil can be expressed as,

$$\tau_f = c_a' + (\sigma_f - u_a)_f \tan 39.3^\circ \quad (3)$$

The variation of apparent cohesion c_a' with the degree of saturation is presented in fig. 3. The decreasing trend of apparent cohesion with increasing degree of saturation can be clearly seen. But with the limited data, it is not feasible to obtain an accurate curve fitting.

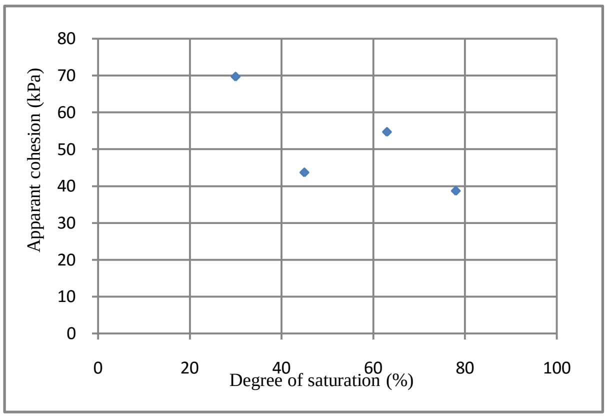

Fig. 3 Apparent cohesion versus degree of saturation

With the increasing degree of saturation, the matric suction, (u_a - u_w), will decrease and approach zero at 100% saturation. There were not enough samples to conduct direct shear tests at 100% saturation. Experiments to develop the soil-water characteristic curve are currently underway but could not be completed.

If the matric suction, (u_a -u_w), is measured during the tests, the ϕ^b value could be obtained.

8 CONCLUSIONS

The aim of this research is to derive the relationship between the apparent cohesion and degree of saturation of residual soil obtained from Welipenna site. A direct shear test was performed on undisturbed residual soil samples under net normal stress ranging from 50 kPa to 200 kPa by varying the degree of saturation of soil specimens. The direct test was chosen over other tests because of shorter drainage path of sample and thus lesser time taken for the pore water pressure to reach equilibrium. The test results were analyzed according to unsaturated shear strength theory proposed by Fredlund and Rahardjo (1993). These results convey that the soil has a friction angle of 39.3˚ associated with net normal stress axis. Also, the apparent cohesion of tested soil decreases with increasing degree of saturation.

The limitations of this study are,

(i) Matric suction could not be measured during the tests.

(ii) Soil- water characteristic curve could not be obtained for the tested soil.

9 RECOMMENDATIONS

The scope of this research is limited to derivation of relationship between the apparent cohesion and degree of saturation of soil. From a practical point of view, monitoring the matric suction is easier than monitoring the degree of saturation of residual soil. In order to produce the relationship between shear strength and matric suction, soil- water characteristic curve for particular soil must be developed. It can be done either by taking field measurements of matric suction using the tensiometer or performing laboratory tests on pressure plate apparatus.

Soil obtained from shallower depth (0.5 m below the ground level) was investigated for its shear strength in the present study. In actual situation, the unsaturated soil properties vary with depth as degree of weathering changes which will ultimately affect the shear strength of soil. Hence, the study must be extended to assess the strength parameters of soil at various depths.

Natural heterogeneity of residual soils raised uncertainty about the similarity of specimens tested in this study. Therefore, repeatability of tests should be done in future to verify the test results.

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