Laboratory Studies on Shear Strength of Expansive Clays

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SYNOPSIS: Generally all clays exhibit linear strength envelopes in terms of effective normal stresses. However, Katti (1978) reported bilinear strength envelopes based on both total and effective normal stresses for expansive soils.

This paper presents results of consolidated drained direct shear tests conducted on Warangal Black Cotton Soil. The shear strength envelopes obtained from these tests confirm the bilinearity in the sense that effective angle of friction ($\emptyset'_1$) for normal stresses upto swell pressure is more than the corresponding value ($\emptyset'_2$) beyond swell pressure. The reasons and implications of such a behaviour are also discussed in the paper.

Soil samples are moulded at three different initial void ratios of 0.9, 0.8 and 0.7 with a moisture content of 10%. They have been subsequently allowed to absorb moisture and swell freely under a nominal surcharge load of 0.07 kg/cm^2 (7 KPa). Thereafter, they have been subjected to consolidation under higher normal loads and subsequently sheared under drained conditions. Bilinearity is observed for all initial moulding void ratios. However, the bilinearity is observed to be more pronounced at lower initial void ratio. It is also observed that the values of $\emptyset'_1$ increase with the decreasing void ratio but $\emptyset'_2$ values decrease with the decreasing void ratios.

1 INTRODUCTION

Mohr's strength theory predicts that shear strength of soil is a function of normal stress. This functional relationship could in general be nonlinear, though Coulomb's linear version is normally used. Terzaghi clarified that effective stress and not total stress is implied in reckoning the normal stress. Thus, linear effective relationship implies the use of two effective shear parameters viz., cohesion (intercept) and angle of internal friction (slope of the strength envelope).

However, for expansive clays, Katti (1978) reported bilinear relationship between strength and normal stress which calls for two additional shear parameters, namely the normal stress corresponding to intersection of two straight lines (σ'_b) and slope of the second straight line ($\emptyset'_2$) which is flatter than the first straight line ($\emptyset'_1$). Katti (1978) further found that σ'_b roughly corresponds to swelling pressure value of the soil and attributes the bilinearity to the structural changes taking place in the soil. Nagaraj et al (1980) attributed the bilinearity to pseudo-equilibrium state of opposite trend existing on either side of swelling pressure. Fredlund (1987) also reported bilinear nature for partially saturated soils.

2 EXPERIMENTAL STUDY

The aim of the present study is to confirm the bilinear nature of strength envelope for Black Cotton Soil of Warangal which is of expansive nature. Representative soil sample collected from Tourist Guest House near Regional Engineering College, Warangal at a depth of 1.5 m has been used. The soil had the following index properties:

Liquid Limit (%)	63
Plastic Limit (%)	24
Shrinkage Limit (%)	10
Freeswell Index (%)	132
Sand (%)	31
Silt (%)	28
Clay (%)	41

The natural soil had been air dried and fraction passing 2 mm was used. Soil was statically compacted with an initial moulding moisture content of 10% to void ratios of 0.9, 0.8 and 0.7. The soil was then allowed to absorb moisture under a normal pressure of 0.07 kg/cm^2 (7 KPa) and allowed to swell completely for nearly 4 to 5 days. Subsequently, the sample was allowed to consolidate under a specified normal stress for 1 to 2 days and sheared under drained conditions in the direct shear test. The consolidation pressures were selected from 0.25 kg/cm^2 to 2.5 kg/cm^2 (this gives a wide range of normal stresses below and above σ'_b values). The volumetric changes during consolidation and shearing stage were measured. The rate of shearing was 0.0125 mm/min. It may be mentioned that Katti (1978) conducted similar experiments on other expansive soils of India, but with one difference that the samples were saturated at constant volume.

3 PRESENTATION AND DISCUSSION OF TEST RESULTS

The results obtained from swelling and consoli-

dation stage are shown in Figure 1. The intersection of pressure-void ratio curve with the initial moulding void ratio line gives the swelling pressure value obtained by the free-swell method.
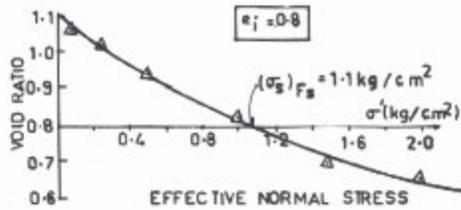

Figure 1. Consolidation curve.

Similarly, swelling pressure values of 0.8 and 1.5 kg/cm² were obtained for soil samples moulded at initial void ratios of 0.9 and 0.7 respectively.

It is seen that the swelling pressure value depends upon initial moulding void ratio, lesser the void ratio more would be the swelling pressure (Chen, 1975).
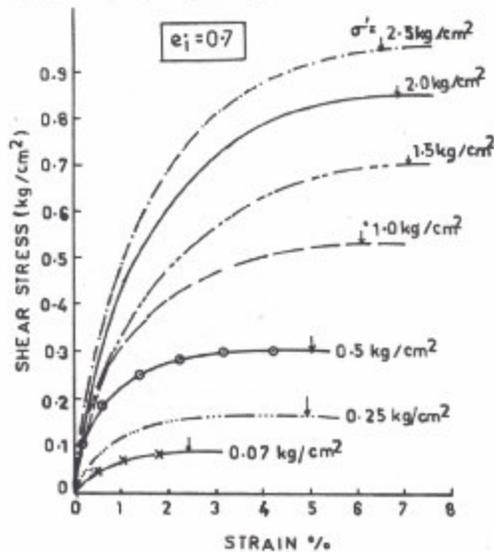

Figure 2. Stress-strain relationships.

Figure 2 gives stress-strain relationships for soil samples tested with an initial moulding ratio of 0.7. The shear stresses were found to be increasing with the increasing axial strain in a hyperbolic form (Kondner, 1963). The arrows in Figure 2 indicate the maximum shear stress values (i.e., shear strength values).

Effective shear strength envelope obtained from samples moulded with initial void ratio of 0.7 is shown in Figure 3, which shows a discerning trend of bilinear relationship.
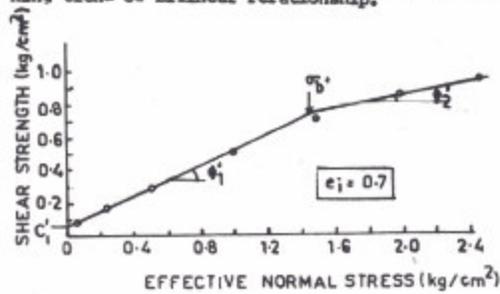

Figure 3. Effective shear strength envelope.

The shear strength formulation for expansive soils can thus be written in the form of the following two equations:

$$s = c'_1 + \sigma' \tan \phi'_1$$
$$\text{where} \quad \sigma' \leq \sigma'_b$$
$$= c'_1 + \sigma'_b \tan \phi'_1 + (\sigma' - \sigma'_b) \tan \phi'_2$$
$$\text{for} \quad \sigma' \geq \sigma'_b$$

The four effective shear parameters obtained from Figure 3 are as follows:

$$c'_1 = 0.06 \text{ kg/cm}^2 \qquad \phi'_1 = 27^\circ$$
$$\sigma'_b = 1.45 \text{ kg/cm}^2 \quad \text{and} \quad \phi'_2 = 12^\circ$$

It may be observed that value ϕ'_1 is nearly twice that of ϕ'_2 and the value of normal stress corresponding to point of intersection σ'_b nearly coincides with the swelling pressure (1.5kg/cm²) value obtained from freeswell method. Similar trend of results were obtained for other moulding void ratios (Table 1). These results are in agreement with the findings of Katti (1978).

Table 1 Effective shear parameters

Moulding void ratio, e_i	0.9	0.8	0.7
Cohesion intercept, c'_1 (kg/cm²)	0.04	0.05	0.06
First angle of internal frction, ϕ'_1 (degrees)	21	23	25
Normal stress at bilinearity σ'_b (kg/cm²)	0.9	1.16	1.45
Second angle of internal friction ϕ'_2 (degrees)	17	14	12

It is seen from the Table 1 that as the moulding void ratios increase ϕ'_1 values decrease while ϕ'_2 values increase, thereby reducing their difference.
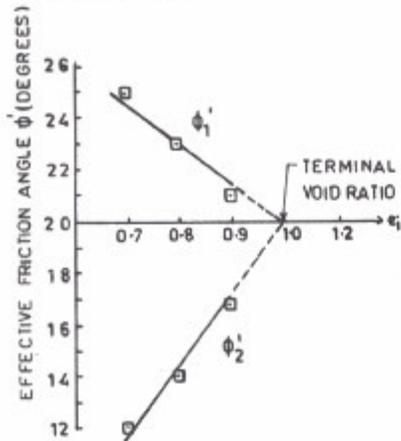

Figure 4. Effective friction angle Versus moulding void ratio.

It is seen from Figure 4 that at a moulding void ratio of roughly equal to 1, ϕ'_2 becomes equal to ϕ'_1. Such value of void ratio may be called terminal void ratio in the sense that if the soil sample is moulded at a void ratio greater than the particular value, the soil virtually does not swell and behaves like a nonexpansive clay without any bilinear trends. This has been confirmed by testing samples with an initial moulding void ratio of 1.1.

The failure envelopes obtained for soil samples tested with moulding void ratio of 0.9, 0.8 and 0.7 are plotted in Figure 5. It can be observed that in spite of bilinearity the failure envelopes are not overlapping (for the range of normal stresses adopted in the tests).
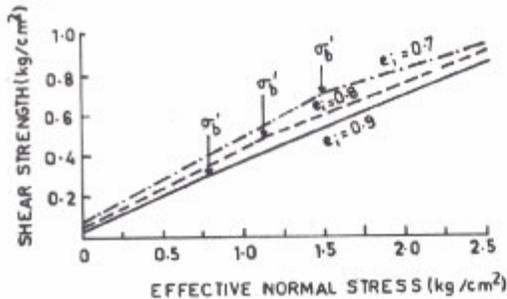

Figure 5. Failure envelopes.

Studies conducted on triaxial consolidated undrained tests with pore pressure measurements (CU) on the above soil also confirmed the similar trends (Nagender Rao, 1989). The pore pressure response during shear in triaxial tests and the volumetric strains observed during the shearing stage of direct shear tests reported in this paper (see Figure 6) indicate that for consolidation (normal) pressures less than swell pressure the expansive soil behaves as a normally consolidated clay with a loose structure, while at higher normal stresses the same soil behaves like a over-consolidated soil with a stiff structure. These structural changes are perhaps responsible for bilinear failure envelopes.
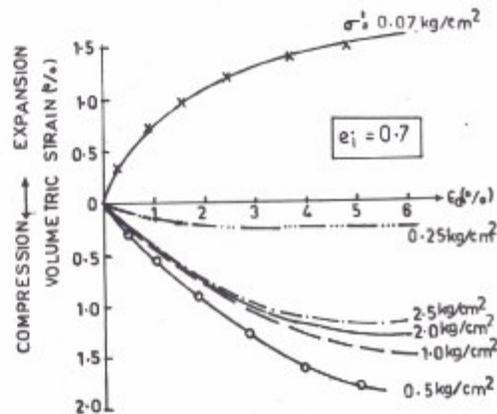

Figure 6. Volumetric strain (%) Versus Axial strain (%).

There are two implications of bilinear strength envelope for expansive soils. Firstly, the shear tests on expansive soils have to be conducted for a wide range of normal stresses (in direct shear tests) or confining pressures (in triaxial shear tests), the values being both on high and low sides of swelling pressure.

Secondly, in the design of foundations on expansive soils, there are two possibilities. In the first case concerning the lightly loaded structures placed on expansive soil, the stresses imposed are less than swelling pressure and hence prediction of heave is of primary concern rather than determination of shear strength. The second case is valid for heavily loaded structures including high earth dams where the load intensities are higher than swelling pressure and hence determination of shear strength and bearing capacity are of prime concern. In the later case the bilinear trends must be confirmed and used in the analysis, lest there is a possibility of over-estimating bearing capacity using ϕ'_1, which is higher than ϕ'_2 in the analysis.

CONCLUSIONS

1. Effective shear strength envelopes for

the soil tested consist of two straight lines instead of a single line commonly found in non-expansive clays. This calls for the use of four shear parameters instead of the traditional two, namely the vertical intercept (c'_1) and the slope (ϕ'_1) of the first straight line, the slope of second straight line (ϕ'_2) and the normal stress (σ'_b) corresponding to the point of intersection of two straight lines.

2. For any given moulding void ratio, σ'_b value roughly corresponds to the swelling pressure of the soil.

3. ϕ'_2 value is found to be less than ϕ'_1 by about 4^0 to 13^0 implying flattening of the strength envelope at higher normal stresses.

4. It is observed that ϕ'_1 values increase with the decreasing void ratio whereas opposite trend is observed for ϕ'_2 values. The value of initial moulding void ratio at which ϕ'_2 roughly equals ϕ'_1, is called terminal void ratio.

5. For expansive clay, the swell pressure as well as σ'_b value decreases with the increasing initial void ratio and hence there is a possibility that at some high initial mould-ing void ratio (called terminal void ratio) the soil may not exhibit any swell pressure and hence bilinearity will not be apparent and the strength envelope will be linear with a slope of ϕ'_2.

6. The bilinearity is attributed to the type of soil structure and the nature of volu-metric changes exhibited during drained shear. For the range of normal stress less than σ'_b, the expansive soils behave similar to normally consolidated clays undergoing higher volume changes and for the normal stresses greater than σ'_b, they behave as over consolidated clays.

7. Prediction of heave is more important than bearing capacity in case of lightly loaded structures on expansive soils. The opposite is true in case of heavily loaded structures inclu-ding high earth dams, hence for the design of foundations of such structures it is imperative that the strength response must be found by test-ing the soil, with the normal stresses exceeding

swelling pressure and appropriate shear parame-ters including ϕ'_2 be used in assessing the bear-ing capacity, lest it may be in danger of being over-estimated if it is based only on ϕ'_1 value.

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