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Investigation on the effect of intermediate principal stress on shear behaviour of unsaturated soils

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ABSTRACT

Directional-dependent properties of the soil, like shear strength, stiffness and hydraulic conductivity, are known as anisotropy in soils. Shape and size of the soil particles and void distribution as microstructure characteristics and external factors such as stress history, environmental and geological conditions, and present stress condition can be the causes of the anisotropy in soils. In this paper, the behaviour of soil has been studied in stress-strain plain under monotonic anisotropic loading to investigate the effect of induced anisotropy on brittleness index of soil sample. The brittleness index of the soil is defined as the difference between the ultimate and peak shear strength divided by the peak shear strength of the soil. The two major parameters describing induced anisotropy or anisotropic loading are intermediate principal stress (b) and principal stress direction (α) which are representative of the difference between intermediate, maximum and minimum principal stresses and the rotation angle of the principal stresses' axis, respectively. This paper only takes the effect of intermediate principal stress with the values of 0.25, 0.5, 0.75. In addition, the soil is in the unsaturated state with the saturation degree of 80% using the constant water (C.W.) method.

Keywords: Unsaturated soils; Induced anisotropy; Saturation degree; September 2023; Hollow cylinder apparatus; brittleness ratio.

1. Introduction

Numerous studies have investigated the anisotropy in soils, which is defines as the directional-dependent characteristics of the soil, and is divided into two types of inherent and induced anisotropy, related to the structure of the soil and the response of the soil to the anisotropic loading, respectively. As a main factor resulting in inherent anisotropy in soils, sample preparation method can bring a highly or moderately anisotropic media (Fig. 1). Induced anisotropy, or anisotropic loading comes to account when principal stresses are not precisely directed in horizontal or vertical directions, or the intermediate principal stress is different than any of the minimum or maximum principal stresses. The latter will cause an intermediate principal stress parameter other than zero according the definition presented in Eq.1

$$b = \frac{\sigma_2-\sigma_3}{\sigma_1-\sigma_3} \tag{1}$$

The effect of stress history has been investigated in many studies (Kinner and Ladd, 1973; Mitachi and Kitago, 1979; Nakase and Kamei, 1983), reporting in anisotropy in strength and deformation characteristics for cohesive soils prepared under anisotropic stress conditions and fabric formations. Altered strength and deformation characteristics due to different principal stresses direction has been reported by reference.

In the field of unsaturated soils Estabragh and Javadi. 2014 investigated the existence of a Roscoe Hvorelev in silty soils with over-consolidated stress history. Their unsaturated results were consistent with the same fundamental of the Hvorslev surface in the saturated soils.

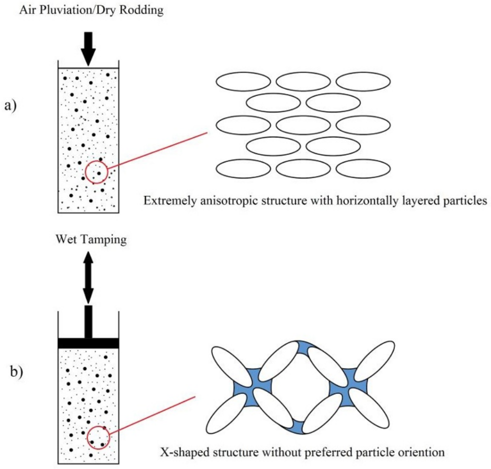

Figure 1. Inherent anisotropy in different sample preparation methods

In this paper, over-consolidation ratio of the sample is taken into account using the definition of the brittleness index defined in Eq.2

$$I_B = \frac{q_{peak}-q_{ultimate}}{q_{peak}} \tag{2}$$

Another study investigating the rate dependence of mechanical properties of unsaturated soils (Toyota, et. al,

2019) has reported that in the range of 0.001%/min to 1%/min, the rate of shear strain does not change neither the shear strength nor the induced anisotropy of unsaturated soils for moisture controlled unsaturated conditions. On the other hand, for suction-controlled conditions, smaller rates of shear strain (0.01%/min and lower) the shear strength and induced anisotropy are both changing with the pace of loading.

Table 1 presents some of the most important papers in the field of induced anisotropy under monotonic loading. Accordingly, in the field of anisotropic behaviour of soils, studies have been concentrating on suction-control in the field of unsaturated soils.

Table 1. Effect of induced anisotropy in the literature

Testing device	Soil Type	α (°)	b (-)	Comments	Reference
DSC	Sand	0, 40, 70, 90	0	$\alpha \uparrow \rightarrow \frac{\sigma'_1}{\sigma'_3} \downarrow$	J.F.R, et al, 1977
HC	Sand	0, 15, 30, 60, 75, 90	0.5	$\alpha \uparrow \rightarrow \frac{\sigma'_1 - \sigma'_3}{\sigma'_1 + \sigma'_3} \downarrow$	Miura, et al, 1986
Biaxial	Sand	0, 15, 30, 60, 66, 75, 90	0.2 - 0.3	$\alpha \uparrow \rightarrow \frac{\sigma'_1}{\sigma'_3} \downarrow$	Oda et al, 1985
HCTS	Sand	15, 30, 45, 60, 75	0.5	$\alpha \uparrow \rightarrow \varphi \downarrow$	Nakata, et al,1998
HCTS	Sand	0, 30, 60, 90	0, 0.5 1	$\alpha \uparrow \rightarrow \varphi_{CSR\downarrow}$	Sivathayalan, et al, 2002

Considering the over-consolidated stress history, the soil response in stress-strain plain will result in a peak and ultimate shear strength according to the soil mechanics. Hence, for a soil sample with OCR>0 the brittleness index will be greater than zero. The sample was prepared with static loading method, and after treatment procedure, anisotropic loading was applied to the soil to study the over-consolidated behaviour of the soil under different values of b (0.25, 0.5 and, 0.75), resulting in 3 samples of Firoozkooh silt samples with the same characteristics of 18% compaction moisture content and 80 % saturation degree. The water flow was prohibited via hydrophobic filter papers assigned to top cap and pedestal to assure constant water conditions. Strain-controlled monotonic loading was applied with vertical strain rate of 1%/min. According to reference, the shear strength of fine graded soils is independent of strain rate between strain rates of 0.001%/min and 1% min. the main goal of this study is to obtain over-consolidated shear behavior of silty samples under anisotropic loading.

2. Experimental Study

2.1. Testing apparatus

The hollow cylinder apparatus, made by Wykeham Farrance International Company (Fig. 2) was used to apply monotonic anisotropic loading with controlling α and b separately.

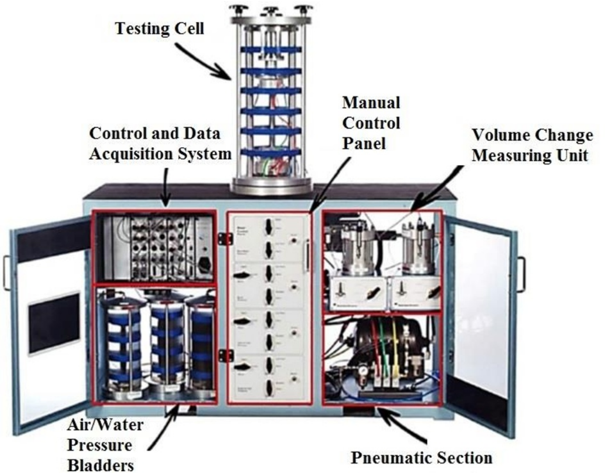

Figure 2. Hollow Cylinder Apparatus

The specifications and accuracy of the devise is presented in Table 1. The constant water situation was assured by using hydrophobic filter papers on the top cap and pedestal to prevent any water flow. Fig. 3 demonstrates different parts of the device and water paths schematically.

Table 2. Specifications and accuracy of the Hollow Cylinder apparatus

Specification	Unit	Value/ capacity	Accuracy
External Dia. of sample	mm	100	-
Internal Dia. of sample	mm	60	-
Height of sample	mm	200	-
Axial Force	kN	±10	0.001
Torque	N.m	±300	0.01
Sample Volume change	ml	±100	0.1
Inner cell volume change	ml	±100	0.1
Vertical disp.	mm	±25	0.01
Radial Disp.	mm	±50	0.0015
Internal/ external water pressure	kPa	1000	0.1

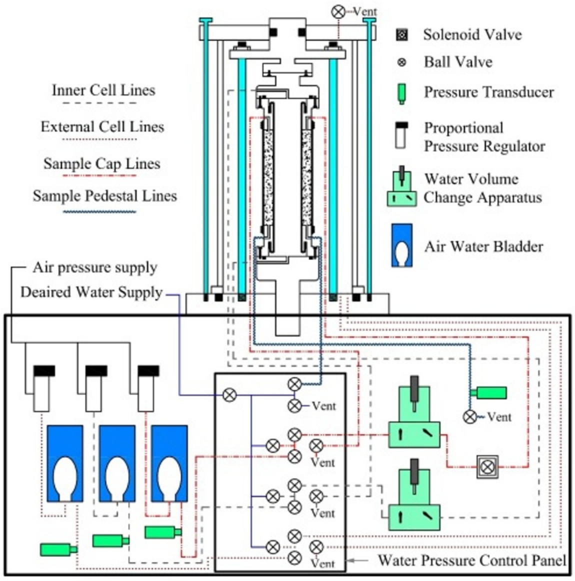

Figure 3. Hollow Cylinder Device

2.2. Testing Material

This study used Firoozkooh silt mixed with bentonite with 10:1 ratio. The physical characteristics of the mixture is summarized in Table3.

Table 3. Testing material properties

Property	Unit	Value	Numbering
G_s	-	2.605	1, 2, 3, etc.
LL	%	23.23	1.1, 1.2, 1.3, etc.
PL	%	30.3	1.1.1, 1.1.2, 1.1.3, etc.
w_{opt}	%	18	
USCS Type	-	ML	ML

2.3. Sample Preparation and test procedure

The hollow cylinder samples in this research were prepared with static compaction method with the moisture content equal to optimum water content of standard compaction test in five layers. After reaching the desired saturation degree of 80%, samples were stored in water proof container under 25 centigrade degrees for one month to assure that every part of the sample has the same saturation degree. After the treatment step, isotropic loading was applied to each sample as the consolidation stage. Finally, anisotropic shear loading was applied with α=15 and b=0.25, 0.5 and, 0.75, and the response of the samples were gathered. Table 4 represents the testing plan for 3 different samples.

Table 4. Test program and parameter value

Test ID	w (%)	S_r(%)	α	b
MHC-b1	14.96	80	15°	0.25
MHC-b2				0.5
MHC-b3				0.75

3. Test results and discussion

3.1. Effects of intermediate principal stress on Brittleness index

Fig. 4 presents the deviatoric stress during shear loading for 3 different values of b. As it can be seen, the maximum q happens when b=0.75. based on the peak and residual values for deviatoric stress. The brittleness index will be calculated.

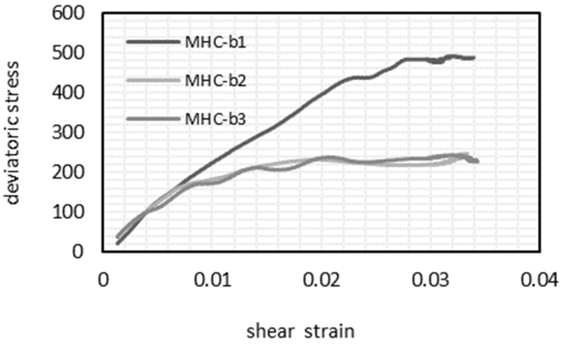

Figure 4. Deviatoric stress during shear loading for different values of b

Fig. 5 indicates the brittleness index against intermediate principal stress for 3 separate values. The results show that $I_B$shows a symmetrical trend against b with its minimum at b=0.5.

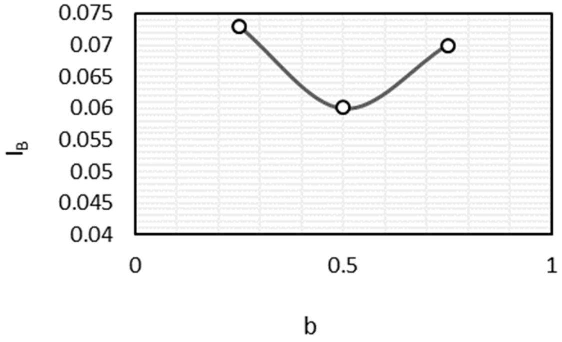

Figure 5. Brittleness Index variation versus Intermediate principal stress parameter

3.2. Unsaturated status variation during shear loading

Fig. 6 demonstrates the saturation degree during the test against shear strain. It can be seen that in each test, the variation of saturation degree has two steps, first being constant (for b=0.25) or slightly constant (for b=0.5 and 0.75) and second slightly constant (for b=0.25) or decreasing (for b= 0.5 and 0.75). This behavior is due to the effect of b on compaction of the sample, meaning that for b=0.25 in the first step the sample has been compacted during shear loading, having a decreasing void ratio and increasing saturation degree. On the other hand, for b=0.5 and 0.75, the sample does not seem to have a significant volume change during the first step and hence, the saturation degree does not change in this step. This analysis can be verified by the void ratio distribution during the test presented in Fig. 7.

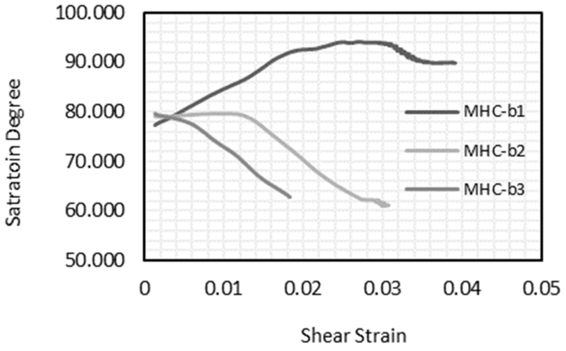

Figure 6. Variation of saturation degree versus shear strain

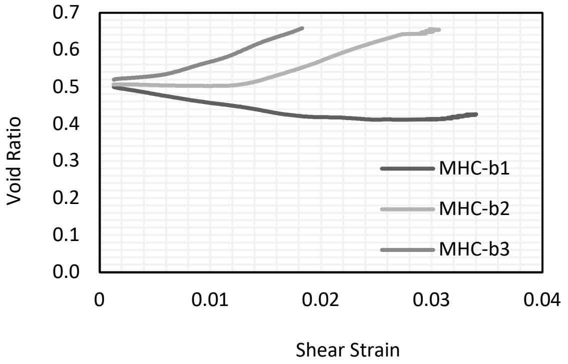

Figure 7. Variation of void ratio against shear strain for different values of b

4. Conclusions

In this paper, 3 hollow cylinder samples using Firoozkooh sand at 80 % saturation degree were subjected to anisotropic loading at an unsaturated hollow cylinder apparatus to investigate the effect of induced anisotropy or anisotropic loading on shear behavior of the soil. Accordingly, the most important results are:

- Brittleness index of the soil is highly dependent on the intermediate principal stress parameter, having a symmetrical trend with its minimum at b=0.5
- The principal stress ratio is highly effective on compression of the sample, the results show that for b=0.25, the sample shows contraction behaviour during shear loading, which has not been seen for b=0.5 and b=0.75.
- The contraction behaviour of the sample will affect the saturation degree and its variation during the test, meaning that for samples experiencing a compaction, the saturation degree increases (b=0.25).

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