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Evaluation of the effects of principal stress direction on shear modulus of unsaturated sand using hollow cylinder apparatus

F. Jafarzadeh, F. Ahmadi Givi & A. Ahmadinezhad
Civil Engineering Department, Sharif University of Technology, Tehran, Iran

ABSTRACT: Determination of soil shear modulus is one of the most controversial topics in unsaturated soil dynamics. Due to the fact that soils have an anisotropic response, the shear strength and stiffness of geological materials are greatly dependent on the principal stress direction and the intermediate principal stress. In this study, the effects of principal stress direction on shear modulus of unsaturated medium-dense sand have been investigated using cyclic hollow cylinder apparatus. Three series of stress-controlled cyclic tests with different fixed principal stress directions were carried out on the sand sample under different values of suction. Results reveal that shear modulus of unsaturated sand is strongly affected by the principal stress direction (α). From $\alpha = 15°$ to 45°, shear modulus decreases independently of the suction level, but from $\alpha = 45°$ to 75° the trend of shear modulus versus α is dependent on the suction value. As a result, the increase of matric suction not only increases the shear modulus of sand but also changes the effect of principal stress direction on shear modulus of unsaturated sand.

1 INTRODUCTION

The mechanical response of soils greatly depends on the direction and magnitude of principal stresses. The term "anisotropy" in soils refers to any soil properties (including strength and stiffness), which is dependent on the direction. The size, shape, and arrangement of the soil particles in addition to the void distribution between them are the most important causes of soil anisotropy (Yang 2013). Environmental and geological conditions during soil deposition are the other factors responsible for natural anisotropy in soils (Jafarzadeh & Zamanian 2013). This type of soil anisotropy is known as *inherent anisotropy*. Another type of soil anisotropy known as *induced anisotropy* occurring after the process of deposition of the soil, and is due to the stress applied to the soil. These two types of anisotropy in soils were first introduced by Casagrande & Carillo (1944), and have been so far investigated by many researchers (e.g. Oda 1972, Arthur et al. 1977, Yamada & Ishihara 1979, Haruyama 1981, Oda et al. 1985, Wong 2003, Hosseininia 2012, Yang et al. 2015).

Hollow Cylinder Apparatus is the best apparatus among all laboratory devices used to investigate anisotropy in soils since it is the only apparatus which is capable of controlling the direction and magnitude of the principal stresses independently. Therefore, many researchers have used this apparatus to study the anisotropic behavior of sand and, moreover, have concluded that principal stress direction has a significant effect on the shear strength and stiffness of these soils (Al-Rkaby et al. 2016).

Oda et al. (1978) have investigated the effect of principal stress direction, α, which is more exactly defined as the inclination of the major principal stress from vertical, on the monotonic behavior of dense Toyoura sand under plane strain condition. They found that the minimum value for deviator stress occurs at α between 60° and 66°.

Miura et al. (1986) conducted a series of drained tests on the dense Toyoura sand using a hollow cylinder apparatus. In their study, monotonic loading applied to the soil specimens with different values of principal stress direction (α = 0º, 15º, 30º, 60º, 75º, 90º) and under the intermediate principal stress parameter, $b = (\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$, equal to 0.5. Their results demonstrated that strength of the soil decreases with an increase in α, its minimum value occurs in a range of α = 60-75°, and strength reverts slightly at α = 90°. Their findings are consistent with the results obtained by Oda et al. (1978).

Guo (2008) reported similar results compared to the studies mentioned above. He conducted a series of tests on sand samples using a modified direct shear device and found that the friction angle decreases by increasing α, reaches to a minimum value at α = 60-65°, and then increases.

Razeghi & Romiani (2015) performed a series of drained tests using a hollow cylinder apparatus in order to study the effects of principal stress direction on the behavior of Firoozkuh sand. They showed that the shear strength decreases by increasing α. It is worth noting that they only investigated the range of α from 0° to 60°.

However, there are some studies not supporting the studies mentioned above. For example, Jafarzadeh & Zamanian (2014) reported an insignificant effect of principal stress direction on internal friction angle at steady state or phase transformation in dense sands.

Very limited studies have been made to investigate the effects of principal stress direction on dynamic properties of sand. Jafarzadeh & Zamanian (2013) and Chaudhary et al. (2002) found that the shear modulus and damping ratio are insignificantly affected by principal stress direction.

Studying the influence of principal stress direction has only been made on saturated sand using hollow cylinder apparatus. Due to the fact that matric suction and degree of saturation have a considerable impact on the cyclic behavior of sand, it is of paramount importance to investigate the effects of anisotropy on the unsaturated sand.

In this study, the effects of principal stress direction on shear modulus of medium-dense sand have been investigated using hollow cylinder apparatus. Three series of stress-controlled cyclic tests with different fixed principal stress directions were carried out on the sand sample under different values of matric suction.

2 TESTED SOIL, INITIAL STATE AND LABORATORY TESTING PROCEDURE

The soil tested in this study is Babolsar sand obtained from the South coast of the Caspian Sea in Mazandaran province, North of Iran. Grain-size distribution curve of this soil is shown in Figure 1. A number of index tests were carried out based on the ASTM standards (ASTM D4253-00, ASTM D4254-00, ASTM D854-02), and physical properties of the soil used in the experimental program are summarized in Table 1.

Hollow cylinder apparatus of Sharif University of Technology, manufactured by Wykeham Farrance International Company, was used for performing the tests. This apparatus has been developed to carry out unsaturated tests on soil samples. Details of the system development have been reported by Hosseinpour et al. (2016).

This apparatus uses a soil sample with an outer diameter of 100 mm, an inner diameter of 60 mm and a height of 200 mm. The wet tamping method using under-compaction technique was adopted for the preparation of the sample with the initial water content of 17% (Ladd 1978). The sample was prepared to obtain an initial relative density of about 30% and then, it was subjected to a confining pressure (σ_m) of 30 kPa prior to cyclic loading.

In this study, three series of stress-controlled cyclic tests were carried out first on the initial state of the sample (without applying matric suction) and then, on the same sample under matric suction of 5 and 9 kPa. Each time the suction was applied to the sample, the volume of water expelled by the sample versus time was measured: when the water exchange reached to 0.1 cc/hour it was assumed that the sample reached moisture equilibrium. Then, the sample was tested with different values of principal stress direction (α = 15º, 45º, 75º). Moreover, during the cyclic loading, the intermediate principal stress parameter (b = 0.5) was maintained constant. The tests were performed with a frequency of 0.1 Hz and the cyclic deviator stress

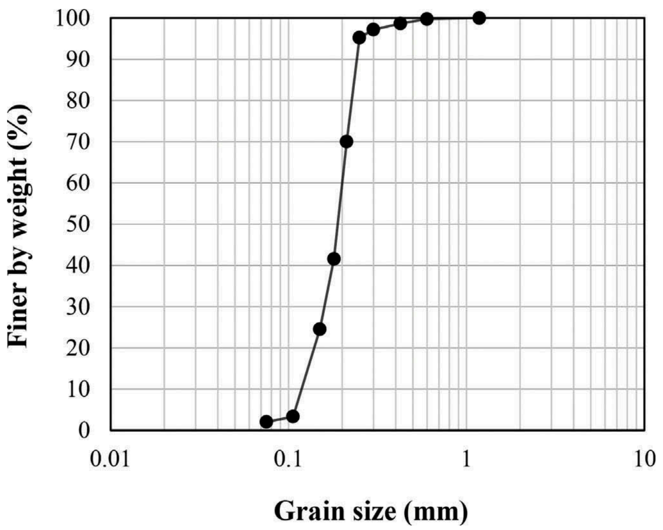

Figure 1. Grain size distribution of Babolsar sand.

Table 1. Physical properties of Babolsar sand.

Physical properties		Measured value	ASTM
Specific gravity	G_s	2.800	D854-02
Maximum void ratio	e_{max}	0.769	D4254-00
Minimum void ratio	e_{min}	0.583	D4253-00

(q) of 3 kPa. The degree of saturation (Sr) of the sample in the initial state (which was prepared with a moisture content of 17%) was 69.5%, and due to the amount of water exchange, reached 36.3 % and 12.7% under matric suction of 5 and 9 kPa respectively. Testing program and conditions are presented in Table 2.

Two fluid phases, air and water, exist simultaneously in unsaturated soils. As well known, the difference between the pore air (u_a) and pore water (u_w) pressures in soil is the matric suction (S) resulting from the interaction between pore water, pore air and the soil solids (Lu & Likos 2000). In this research, the hanging column technique has been used to apply and control matric suction. In this method, the pore air pressure is atmospheric, and the

Table 2. Testing program and conditions.

Test No.	σ_m (kPa)	q (kPa)	b	S (kPa)	α (°)	Sr (%)
1				2.5 (Initial State)	15	69.5
2					45	
3					75	
4				5	15	36.3
5	30	3	0.5		45	
6					75	
7				9	15	12.7
8					45	
9					75	

negative pore water pressure is applied to the soil sample by changing the water level in the hanging column. Due to the limitation of height, matric suction up to 10 kPa could be applied to the sample using this method. Moreover, the water exchanged by the sample has been measured using the hanging column system with high precision. Furthermore, the volume-change device has been used to measure the sample volume variations in order to determine its relative density. The relative density of the tested sample has reached up to about 40% at the end of the final test.

3 TEST RESULTS AND DISCUSSIONS

As mentioned earlier, matric suction was controlled in the second and third series of the tests. However, for the first series of the tests (initial state of the sample), the negative pore water pressure was measured using two tensiometers at the top and the bottom of the sample and turns to a matric suction of 2.5 kPa on average. Figure 2 shows the soil-water retention curve resulting from the tests.

It is worth noting that every test was performed in 10 cycles. Shear stress-strain curves for test number 8 is shown as an example in Figure 3. According to Jafarzadeh & Sadeghi (2012), the value of shear modulus (G) for each cycle was calculated as:

$$G = \frac{\tau_c}{\gamma_c} = \frac{\tau_{\gamma_{\max}} - \tau_{\gamma_{\min}}}{\gamma_{\max} - \gamma_{\max}} \tag{1}$$

where G = secant shear modulus; τ_c = shear stress; γ_c = shear strain; γ_{max} and γ_{min} are maximum and minimum shear strains respectively; and $\tau_{\gamma max}$ and $\tau_{\gamma min}$ are shear stresses corresponding to the maximum and minimum shear strains. Due to the fact that the variations of shear modulus in 10 cycles are very small, this parameter is reported as the average of 10 cycles in the paper.

Variations of shear modulus versus principal stress direction for the initial state of the sample, and the sample under matric suctions of 5 and 9 kPa are illustrated in Figure 4. As shown in the figure, for the initial state of the sample, in which the soil is closer to the saturated state, by increasing α, shear modulus decreases and reaches to the lowest value at α = 75°. As mentioned previously, many researchers showed that shear strength of saturated sand decreases with an increase in α, and the minimum strength occurs in the range of α = 60-90°. According to the results obtained for the initial state of the sample, this trend is also valid for

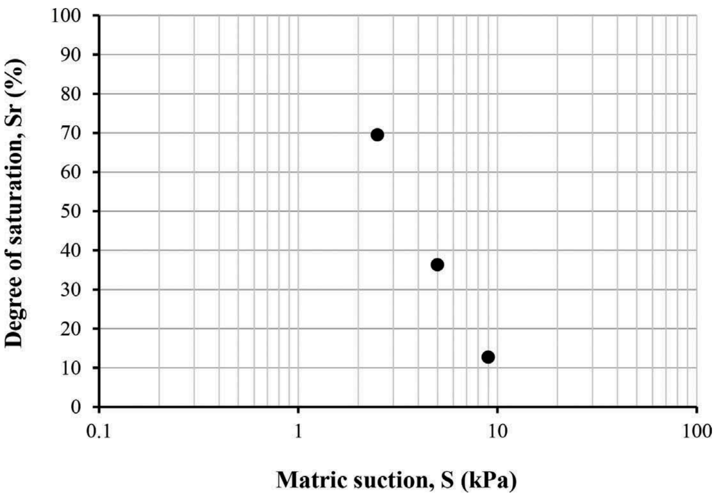

Figure 2. Soil-water retention results for the tested sand.

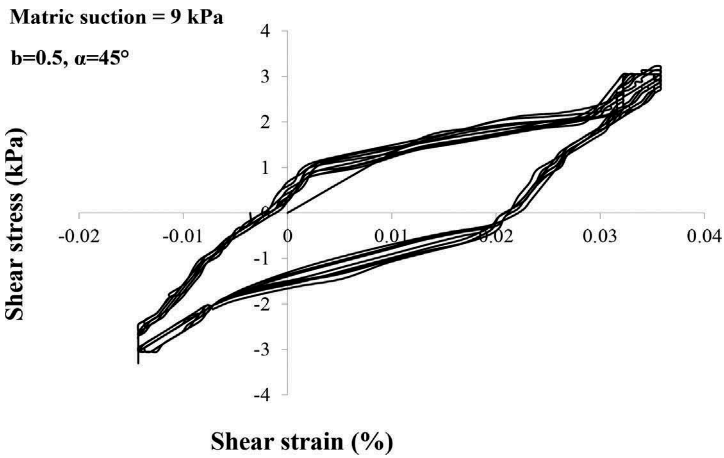

Figure 3. Shear stress-strain curves for test number 8.

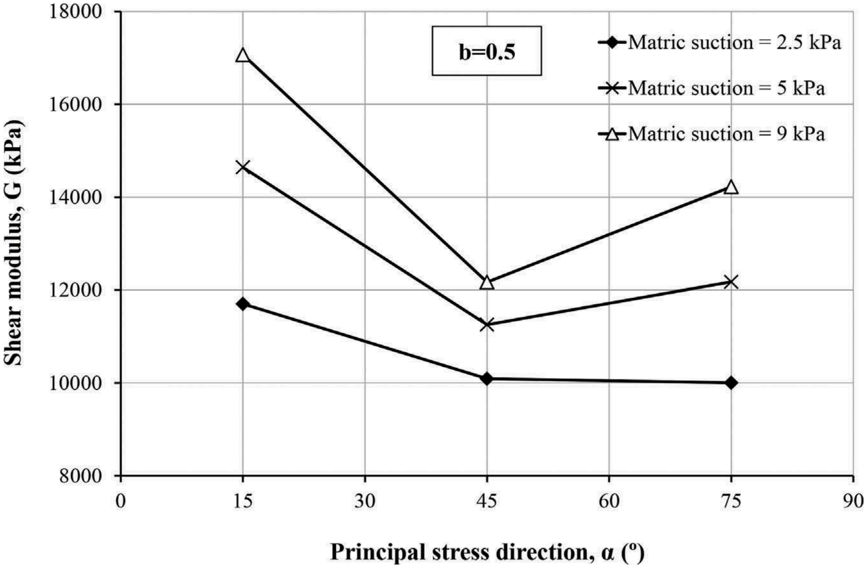

Figure 4. Variations of shear modulus versus principal stress direction.

the variations of shear stiffness. However, such a trend is not observed for the sample under matric suctions of 5 and 9 kPa. As shown in Figure 4, for these testing conditions, shear modulus decreases, reaches its minimum at $\alpha = 45°$ and then increases at $\alpha = 75°$. Moreover, it can be stated that for the sample with the higher level of matric suction, by increasing α from 15° to 45°, shear modulus decreases with a higher rate.

According to the data presented in Figure 4, it can be also concluded that shear modulus at a given α is larger for the sample under a higher level of matric suction. In order to better understand the impact of matric suction on shear modulus, variations of shear modulus versus matric suction for different values of principal stress direction are illustrated in Figure 5: shear modulus increases as suction increases for all the values of principal stress direction. Moreover, the maximum values of the shear modulus were obtained at $\alpha = 15°$.

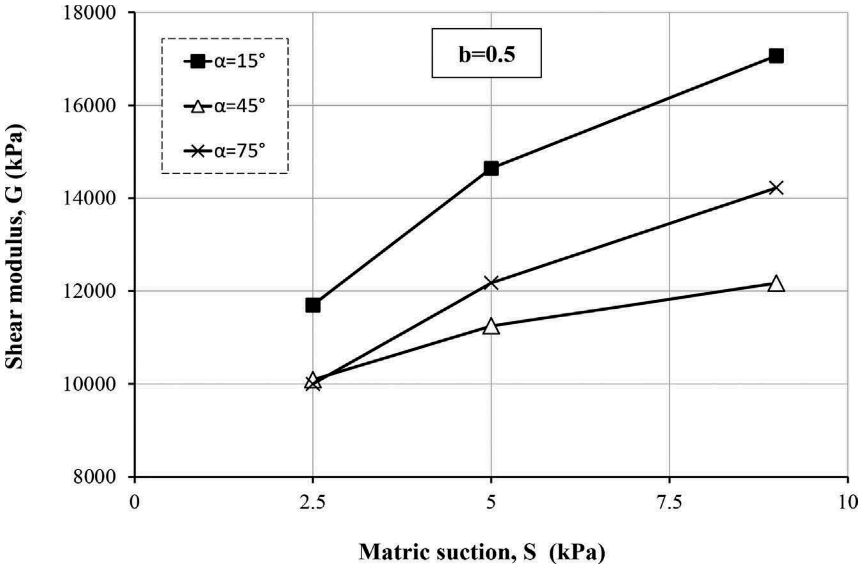

Figure 5. Variations of shear modulus versus matric suction.

4 CONCLUSION

Stress-controlled cyclic tests were carried out on an unsaturated sand using hollow cylinder apparatus in order to investigate the effects of principal stress direction on shear modulus. The results demonstrate a relevant effect of principal stress direction on the shear modulus of unsaturated sand. In all three series of tests, by increasing α from 15° to 45°, the shear modulus decreases, but from α = 45° to 75° the trend depends on the suction value. For the initial state of the sample, the minimum value of shear modulus occurs at α = 75°, but by increasing matric suction, shear modulus reverts at α = 75°. The rate of variations of shear modulus versus principal stress direction is low in the initial state of the sample, but it becomes higher with increasing matric suction. Consequently, it can be stated that shear modulus of sand is significantly affected by the changes in matric suction, and the increase of matric suction not only increases the shear modulus of sand but also changes the effect of principal stress direction on shear modulus of the tested sand.

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