Effect of stress anisotropy on cyclic behavior of dense sand with dynamic hollow cylinder apparatus

Effet de l'anisotropie de contrainte sur le comportement cyclique du sable dense avec dynamique appareil cylindre creux

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ABSTRACT: It is well known that soils have an anisotropic response and collapse can be induced by imposing different modes of shearing. Changing the inclination and magnitude of the major principal stress with respect to the depositional direction in most cases will increase the collapse potential and brittleness as well as reduce the shear strength and shear stiffness. In this study the effect of stress path with changing in direction of the major principal stresses on the cyclic behavior of Babolsar sand is studied. A series of cyclic undrained tests on dense sand samples with induced anisotropy were conducted with an automatic dynamic hollow cylinder apparatus. Results showed that inclination of the major principal stress with respect to the depositional direction has significant effect on samples responses to the cyclic load. Because of the differences of the sand particles interlock in various directions, the sand strength parameters changes with loading direction. Changes in loading direction would change the specimens stress status and would cause different deformation pattern. This kind of stress anisotropy had not significant effect on shear modulus and damping ratio.

RÉSUMÉ: Il est bien connu que les sols ont une réponse anisotrope et que l'effondrement peut être induit en imposant différents modes de cisaillement. La modification de l'inclinaison et de l'intensité de la contrainte principale majeure par rapport à la direction de sédimentation va, dans la plupart des cas, augmenter le potentiel d'effondrement et la fragilité ainsi que réduire la résistance au cisaillement et la rigidité de cisaillement. Dans cette étude, l'effet du chemin de contrainte avec évolution dans le sens de la contrainte principale majeure sur le comportement cyclique du sable Babolsar est étudié. Une série d'essais non drainés cycliques sur les sables denses avec anisotropie induite a été réalisée avec un appareil automatique dynamique cylindre creux. Les résultats ont montré que l'inclinaison de la contrainte principale majeure par rapport à la direction de dépôt a un effet significatif sur les réponses des échantillons à la charge cyclique. La direction de chargement change les paramètres de la résistance du sable, en raison de la variation des connexions entre des particules dans les différentes directions. Le changement de la direction du chargement peut changer l'état de la contrainte qui peut produire différents chemins de déformation. Ce type de contrainte anisotrope n'avait pas d'effet significatif sur le module de cisaillement et sur le taux d'amortissement.

KEYWORDS: stress anisotropy, major principal stress direction, sand, cyclic loading, hollow cylinder tests.

1 INTRODUCTION

Soils are anisotropic materials. Environmental and geological conditions during the deposition of the soils, along with the particle shapes, sizes, and void structures are some factors constituting the natural anisotropy of the soil. The fabric of the soil may later be disturbed (further anisotropy) with application of loads and, thus, plastic strains. Casagrande and Carillo (1944) distinguished these two sources of anisotropy as inherent and induced anisotropies; respectively. Inherent anisotropy is impacted by the particle shapes and depositional conditions and is independent from strains. Induced anisotropy is the reconfiguration of the soil fabric to withstand the applied loads. Oda (1972) assessed the initial fabric (inherent anisotropy) of sands and its effect to the mechanical behavior. He used four different sands with different roundness and concluded that the orientation depends on the particle shape and the method of compaction.

Many researchers have used the Hollow Cylinder (HC) apparatus to investigate the cyclic behavior of sandy soils. However, the boundary conditions in these studies varied greatly and the primary focus was on regenerating simple shear conditions rather than systematically investigating the effect of principal stress rotation and intermediate principal stress on the cyclic behavior of sands.

Tatsuoka et al. (1986) designed a torsional hollow cylinder testing apparatus that could cyclically shear the specimens under undrained simple shear conditions by preventing any axial strain development and inner cell volume change. These boundary conditions eliminated changes in the inner and outer radii during shearing. The effect of continuous principal stress rotation was observed only at small strains below 0.2 %. Above this strain level, the effect of continuous principal stress rotation was negligible.

Yamashita and Toki (1993) conducted undrained cyclic triaxial and torsional HC tests on sand specimens. The major principal stress rotation was not varied in a controlled manner and was somewhere between 0° or 90° from the vertical. They found that the cyclic strengths obtained from cyclic triaxial tests and torsional HC tests were not equal and the difference may be more pronounced depending on the sample preparation technique.

Shibuya et al. (2003) investigated the effect of inclination of the major principal stress form vertical, α; and intermediate principal stress ratio, $b=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$; on the monotonic and cyclic behavior of sands. The pore pressure response of the sand subjected to these stress paths showed that large pore pressures are generated due to continuous principal stress rotation at constant deviator stress, $(\sigma_1-\sigma_3)/2$. Changes in b also caused changes in excess pore pressures, but the changes were not as significant as the ones created by the continuous principal stress rotation.

Altun et al. (2005) used a cyclic torsional simple shear apparatus similar to the one used by Towhata and Ishihara (1985). They investigated the cyclic undrained behavior of sandy and silty soils. Their testing program did not include investigation of the effect of either α or b on the cyclic behavior of sandy or silty soils.

Many other researchers have shown that the undrained shear strength of the sandy soils decreases with the increase in α

(Broms and Casparian 1965, Symes et al. 1984, Uthayakumar and Vaid 1998, Sivathayalan and Vaid 2002). Therefore; the more critical location may be away from the foundation centerline, even though the major principal stress magnitude is less compared to the one below the centerline.

Considering the inadequacy and also the inherent limitations of CT (Cyclic Triaxial) and CSS (Cyclic Simple Shear) tests, cyclic HC tests have gained more popularity for the investigation of the effect of cyclic loads on the soil behavior (Ishihara and Yamazaki 1983, Tatsuoka et al. 1984, Ishihara et al. 1985, Tatsuoka et al. 1986, Koester 1992, Altun et al. 2005).

In this study the effect of changing in intermediate principal stress ratio (b) on cyclic behavior and dynamic parameters of Babolsar sand has been investigated. In all tests the direction of the major principal stress was kept in vertical direction (α=0) and intermediate principal stress ratio changed from a test to another one to cover the range of variation of b value. For a closer look of this trend, tests were conducted in two different mean normal effective stresses.

2 EXPERIMENTAL APPARATUS

Advanced testing of geomaterials requires accurate control of loads or deformations. Recent advances in the manufacturing of testing equipment have eliminated the role of the operator in modern systems. Most tests are conducted via closed loop control mechanisms, which may involve servo hydraulic or servo pneumatic systems. The closed-loop control system of the dynamic HC apparatus used in this study has five main components: (1) HC software, (2) high-speed data acquisition system (DAS), (3) servo valves, (4) vertical and horizontal actuators, and (5) load, pressure and displacement transducers.

The apparatus used in this study is made by Wykeham Farrance International Company.

3 SAMPLE PREPARATION AND TESTS PROCEDUR

The original material used in this study was Babolsar sand obtained from Caspian Sea coast in Babolsar, Iran. This uniform sand was sieved to get the tested material, which has mean particle diameter D_{50} = 0.22 *mm*, effective particle diameter D_{10} = 0.14 *mm*, a minimum void ratio e_{min} = 0.543 and a maximum void ratio e_{max} = 0.820. The particles image is illustrated in Figure 1. In this picture the grain size and shape of Babolsar sand particles are evident. It is clear that particles are in the same size and partly angular. Grain size distribution of this sand is shown in Figure 2. This sand classified as poorly graded sand, SP; according to the Unified Soil Classification System. The wet tamping method was used for preparation of the samples. The samples were prepared to obtain relative densities in the range of Dr = 22% ~ 25% after consolidation.

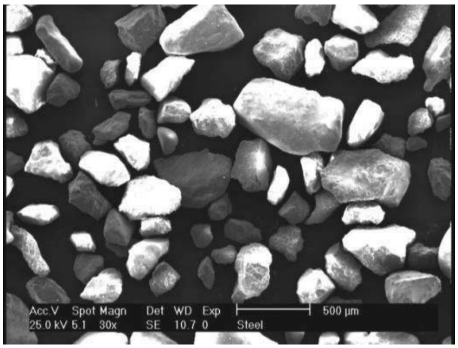

Figure 1. Particles image of Babolsar sand.

After construction of the samples, first CO_2 gas and then de-aired water are passed through them. Next stage includes the full saturation of the samples by applying inner, outer and back pressure increments. This stage will continue to reach the B value more than 0.94.

After that, the samples were isotropically consolidated to reach 150 kPa mean normal effective stress.

Induced cyclic deviator stress was imposed under stress controlled condition. In all tests the rate of induced cyclic deviator stress to initial mean normal effective stress set as 0.27.

For keeping α and b constant during loading, the vertical load and torque values were applied simultaneously as a cycle.

The purpose of this study is to investigate the effect of stress anisotropy caused by changing in principal stress direction on dynamic behavior of sand. 5 tests under controlled state of principal stress direction were conducted.

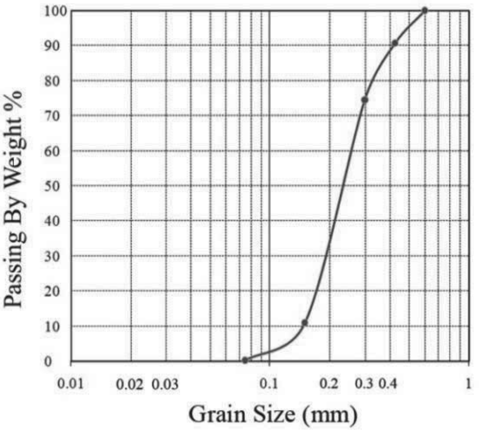

Figure 2.Grain size distribution of Babolsar sand.

In these tests the inner and outer cell pressures were same, therefore; the intermediate principal stress parameter is related to the principal stress direction by Eq.1.

$$b = \sin^2(\alpha) \qquad (1)$$

Detail information of the specimens and their loading details for the mentioned tests are shown in Table 1.

Table 1. Detail information of the specimens

Specimens Id.	*Dr(%)*	*σ'₀ (kPa)*	*α (degree)*	*b*
15010	83	150	10	0.03
15030	87	150	30	0.25
15045	84	150	45	0.5
15060	83	150	60	0.75
15080	86	150	80	0.97

4 TEST RESULTS AND DISCUSSIONS

The maximum shear stress in an element of hollow cylinder samples is a resultant of two shear stresses. The first is a shear stress arisen from torque (τ_{zh}) and another is result of vertical and horizontal stresses difference ((σ'_z-σ'_h)/2) or deviator stress. The maximum deviator stress can be calculated from (σ'_1-σ'_3)/2. As it was mentioned before, in these tests the samples are in the same condition of fabrication and consolidation and the cyclic load are imposed on the specimens under the controlled state of the α and the rate of maximum deviator stress to mean normal effective stress ((σ'_1-σ'_3)/2σ'_0). Figure 3 shows these stress paths of torsional shear stress and deviator stress. With regard to Figure 3, during a test, the specimens are in triaxial compression and triaxial extension state at α=10^o and 80^o loading condition, respectively; and α=45^o is associated by pure shear state.

Figure 4 shows the excess pore water pressure ratio (r_u) generation with shear deformation in tests with different α.

Results show that pore water pressure generation trend has three phases. In the first phase, the pore water pressure generation occurred without any significant shear deformation and the specimens tolerate the cyclic load to reach the $r_u = 0.8$.

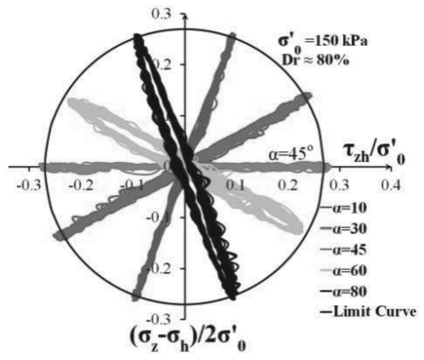

Figure 3. Stress paths of torsional shear stress and deviator in tests

In the second phase, by increasing of the pore water pressure, the specimens lose their stiffness and show a higher deformation more than ten times comparing to the first phase. The third phase is the failure of the specimens, which is accompanied with $r_u \approx 1$.

Unlike other tests, the r_u exceeded from 1 in the samples tested at $\alpha=10$ and 80 loading condition and their failure phase occurred at γ/γ_1 of about 30 clearly. γ_1 is shear strain corresponding to the first cycle. This cyclic response of specimens is the result of the fact that tests were carried out in stress controlled condition. At triaxial compression and extension, the main part of the strain is result of axial and radial strain and the shear portion of the strain is lesser. This kind of deformation causes a brittle response of the specimens.

There are no separation in second and third phases of pore water pressure generation trends in the samples tested at $\alpha=30$, 45 and 60. The failure of these specimens is accompanied with shear deformation. So the samples tested at $\alpha=30^o$, 45^o and 60^o show a softer response to the cyclic loads.

The stress path of deviator stress and mean normal effective stress have been shown in Figure 5. As it shown in this figure, the stress anisotropy has a great effect on stress path and the cyclic responses of the same samples tested at different α.

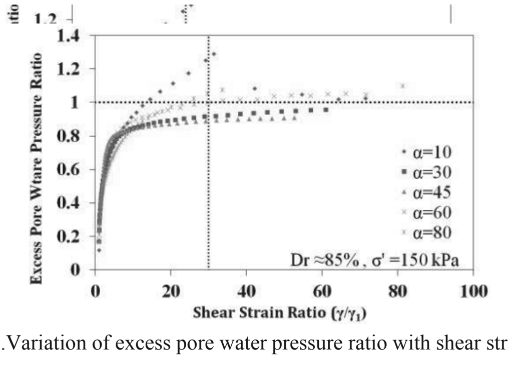

Figure 4.Variation of excess pore water pressure ratio with shear strain ratio

As it mentioned before, α and b were kept constant during a test. So the reciprocal nature of cyclic loads would not change the triaxial compression, triaxial extension or pure shear state of the specimens. Therefore; the failure cover limits of a test were related to the loading and reloading phase of the cyclic load. With respect to the situation of sand particles, loading reversion will change the sand particles interlock.

The sand particles interlock is very sensitive to the loading direction as the slope of failure limit line would be changed at different α, even during a load reversion phase.

Variations of strains in the first and fifteenth cycle of loading are shown in Figure 6. Regarding to the nature of cyclic load, at triaxial compression and extension tests, the axial strain (ε_z) is the major part of the specimens strain.

Because of the relative density of the specimens, the expansive behavior is the expected response.

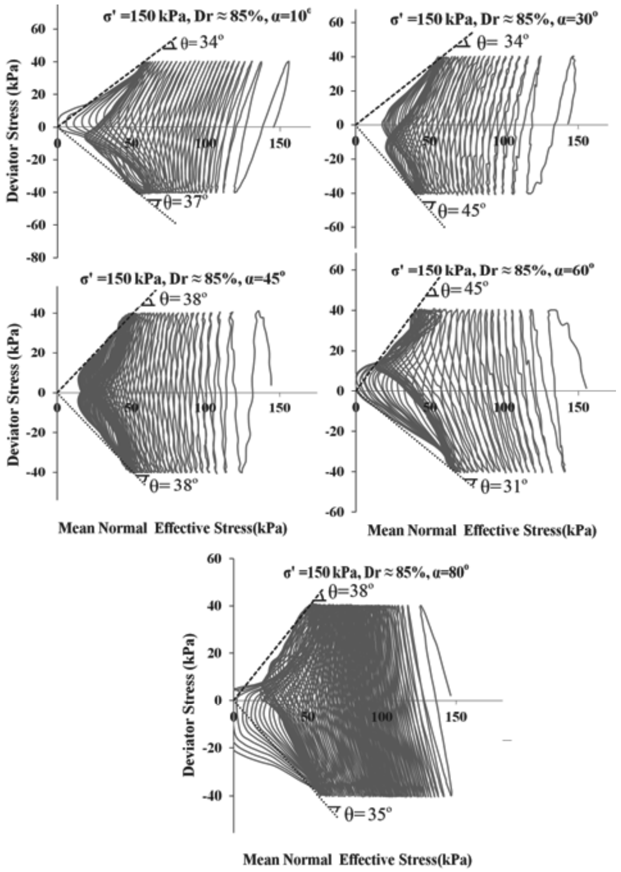

Figure 5.Stress paths of deviator and mean normal stress

At $\alpha=10^o$ loading conditions the cyclic loading and reloading had been imposed through the axial and radial load and the specimens shows a vertical contractive responses to the cyclic load, unlike the other tests. Expansive behavior of this test at radial direction is result of its vertical contractive deformations.

The horizontal shear strains (ε_θ) of the specimens are in the similar trend, but their quantity reduces by approaching α to the 45^o.

The pure shear nature of test at $\alpha=45^o$ causes a higher octahedral shear strains (γ_{oct}). By increases and decreases of α from 45^o, γ_{oct} would be decreased.

The variations of shear modulus and damping ratio of the specimens have been shown in the Figures 7 and 8. The shear modulus and damping ratio have been normalized with their initial values. Results show that stress anisotropy had not significant effect on stiffness reduction and damping ratio of the dense specimens.

5 CONCLUSION

A series of undrained cyclic torsion shear tests on dense sand samples using hollow cylinder apparatus were performed for the purpose of investigating the effect of stress anisotropy on cyclic behavior of Babolsar sand.

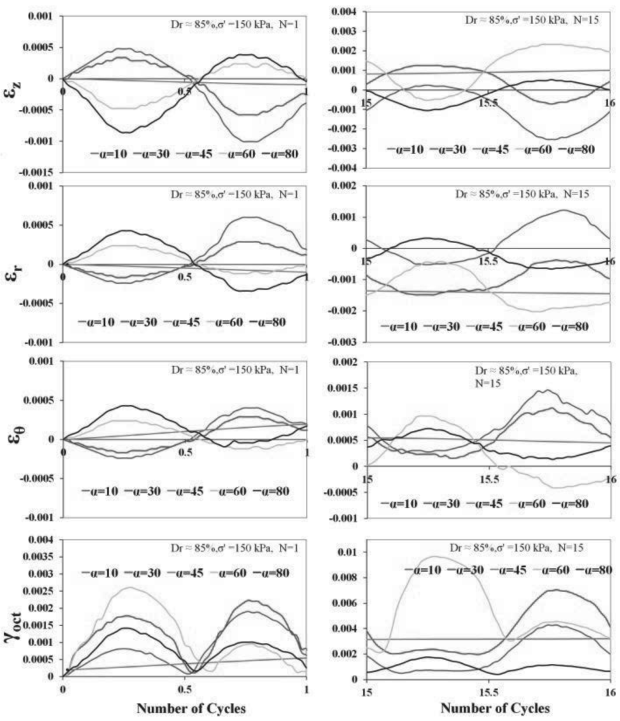

Figure 6. Strains Changes variation through the first and fifteenth cycle

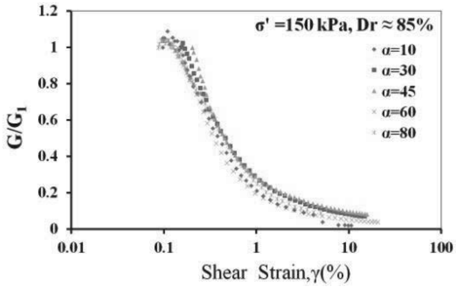

Figure 7.Shear modulus ratio changes with shear strain

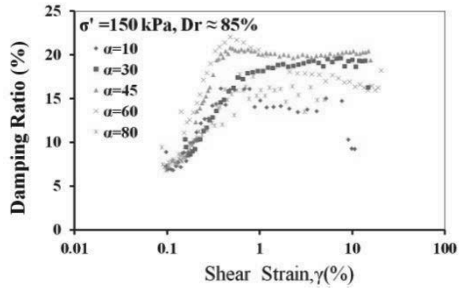

Figure 8. Damping ratio changes with shear strain

In all tests the direction of the major principal stress and intermediate principal stress varies for various tests, but kept constant during each specific test. The response of samples has been investigated under constant loading direction and deviator stress. Results showed that stress anisotropy has significant effect on soil response and the excess pore water presure generation. At triaxial compression (α=10°) and triaxial extension (α=80°) tests the specimens resist over excess pore water pressure build up.

Test results show that the sand anisotropic behavior will be magnified by changing the principal stress direction. In a test under a constant condition of α, b and loading magnitude, the shear strength could be higher in a direction than in its opposite direction. This difference in directional strength of the sand is maximum in some loading directions (α=10° and 80°) and minimum in α=45°. These differences are result of the direction dependent interlock of the sand particles and come from the sedimentary condition.

By changing α, the loading condition of the specimens will be changed. These changes in loading condition by affecting on the specimens strain pattern would cause different responses. As for the α=10° and 80° tests, the main part of the specimens deformation result from axial or radial strains and the shear strain is the major part of strain in specimen tested at α=45°.

This type of stress anisotropy had not significant effect on shear modulus and damping ratio of the specimens.

This kind of anisotropy come from the induced stress status (induced anisotropy) and will be magnified by the directional dependent properties of sand interlocks (inherent anisotropy). So the separation of inherent and induced anisotropy effects may have not been simply possible.

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