Scientia Iranica A (2014) 21(6), 1750–1761

SCIENTIA IRANICA

Sharif University of Technology
Scientia Iranica
Transactions A: Civil Engineering
www.scientiairanica.com

Effect of fabric and initial stresses on the anisotropic behavior of sand

H.R. Razeghi* **and H. Mohamadzadeh**

School of Civil Engineering, Iran University of Science and Technology (IUST), Narmak, Tehran, P.O. Box 16765163, Iran.

Received 9 December 2012; received in revised form 24 January 2014; accepted 6 May 2014

KEYWORDS
Inherent anisotropy;
Initial stress state;
Firoozkuh sand;
Hollow cylinder apparatus;
Drained behavior;
Principal stress rotation.

Abstract. This study investigates the anisotropy in the stress-strain-strength behavior of Firoozkuh sand, focusing on the effect of the initial stress state and soil fabric. The experiments are performed using a hollow cylinder apparatus. Different initial conditions are considered by maintaining the principal stress ratio (i.e. $R_c = \sigma'_{1c}/\sigma'_{3c}$) and the inclination of initial principal stress (i.e. α_c) during consolidation. The specimens are prepared using two different methods to assess the influence of soil fabric. The direction of increments of principal stresses, $\alpha_{\delta\sigma}$, is controlled to remain constant during the test. Generally, the results showed a decrease in the shear strength of sand by increasing $\alpha_{\delta\sigma}$. In specimens consolidated under the inclined anisotropic stresses, the trend of shear strength variation versus $\alpha_{\delta\sigma}$ differed and depended on α_c. The vertical consolidated sands ($R_c = 2$, $\alpha_c = 0$) were found to be highly influenced by $\alpha_{\delta\sigma}$. The anisotropic behavior of medium dense sands was observed to be strongly dependent on the initial stress state. The results showed that the stress-strain behavior of specimens prepared by the wet tamping method is strongly influenced by $\alpha_{\delta\sigma}$. The effect of soil fabric and initial stress state on the shear modulus was more noticeable than that on the shear strength of sand.

1. Introduction

During the last two decades, the effect of anisotropy on the behavior of sand under both drained and undrained conditions has been investigated in several studies using torsion shear tests with stress rotation. Several recent experiments, such as Wijewickereme and Vaid [1], Lade et al. [2], Kumruzzaman and Yin [3], Yu et al. [4], and Doanh et al. [5] have been conducted to study the influence of the rotation of principal stresses on the undrained behavior of sands. Lade [6] studied the anisotropic behavior of sand in a drained condition to investigate the influence of the cross-anisotropic fabric on the shear band inclination and shape of the failure surface.

Few studies have investigated the influence of initial stress anisotropy on the mechanical behavior of medium dense sand under the drained condition during loading. Symes [7] carried out drained tests on water-pluviated Ham River sand in a hollow cylinder apparatus. Isotropically consolidated specimens were sheared by various values of α and b to investigate the effects of initial anisotropy. The shear strength reduced dramatically as the direction of the major principal stress rotated from the vertical. In addition, the value of φ'_{peak} exhibited a dramatic decrease of nearly 12°, as α rotated from 0° to 90°. Wong and Arthur [8] sheared dense samples of Leighton Buzzard sand using the Directional Shear Cell (DSC) with constant $b = 0.4$, and with different orientations of the major principal stresses, with respect to the direction of deposition.

*. *Corresponding author. Tel.: +98 21 77240102; Fax: +98 21 77240398*
E-mail addresses: razeghi@iust.ac.ir (H.R. Razeghi); hmohamadzadeh@iust.ac.ir (H. Mohamadzadeh)

Their results were similar to those of Symes [7]. In these tests, stiffness was also observed to decrease with increasing α. Similar results were observed in other studies, such as Arthur and Assadi [9] and Oda et al. [10], which used plane strain and true triaxial devices. Cai [11] investigated the influence of principal stress rotation on the behavior of drained Portway sand using a hollow cylinder apparatus. The specimens were prepared using the water pluviation method and were isotropically consolidated before shearing. The shear strength and dilative behavior of sand reduced as a rotated from 0° to 90°. However, because most previous experiments were conducted on isotropic consolidated specimens, no comprehensive laboratory tests or good data exist that investigate anisotropy in the behavior of anisotropic consolidated sands.

Rolo [12] investigated the stress-strain-strength anisotropy of a K_0-consolidated soil mixture. After the consolidation phase, rotational shear stresses were increased under an undrained condition to rotate σ_1' from 0° to α which was constant during the loading phase. Comparable stress paths were applied in other studies, such as Menkiti [13], Zdracovic and Jardine [14], Shibouya et al. [15] and Fondokous [16], to keep the amount of α and intermediate principal stress ratio (i.e. b) constant during the loading of the K_0-consolidated specimens. Sivathayalan and Vaid [17] investigated the behavior of sand subjected to anisotropic initial stresses using a hollow cylinder apparatus to maintain the amount of parameters, α and b, during the undrained shearing phase. The results showed that undrained loading might trigger a sudden flow deformation in loose sand. The potential for such flow deformation increased with an increase in initial static shear and higher initial α_σ.

In real problems, soil is subjected to multi-axial loading, which involves simultaneous increases in shear stress levels and the rotation of principal stress directions. Despite its common occurrence in the field, little research has been conducted to study the response of sands under a simultaneous increase in shear stresses and a rotation of principal stress directions. Wijewickereme and Vaid [1] derived a detailed examination of the database on the behavior of loose sand under simultaneous linear increases in effective stress ratio, R, and principal stress rotation, α. However, in real problems, such as shallow foundations, α does not have a linear relation with R. It seems that, in practice, most stress paths are comparable with those used by Nishimura [18], which employ a different approach using a hollow cylinder apparatus to study the anisotropic behavior of clayey specimens consolidated with anisotropic initial stresses. The direction of increments in principal stresses during the loading phase ($\alpha_{\delta\sigma}$), regardless of the stress condition in the consolidation phase, was controlled to be constant. The value of b changed under undrained conditions after consolidation ($R_c > 1$) from 1 to a desired value, with constant mean effective stress (i.e. σ_m'), R_c and α_c. The undrained b-change was followed by constant-b undrained shear with a controlled direction of the principal stress increment axis, $\alpha_{\delta\sigma}$. The stress paths are, therefore, linear in the $\tau_{z\theta} - (\sigma_z - \sigma_\theta)/2$ plane, as illustrated in Figure 1.

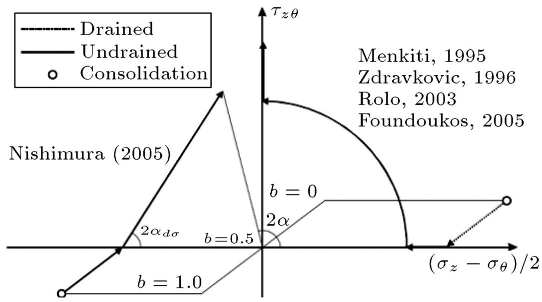

Figure 1. Stress path used by Nishimura (2005) [18] in comparison with other studies.

Tsomokos and Georgiannou [19] investigated the effect of grain shape and angularity on the undrained behavior of sand with similar grading curves. Changing loading conditions from undrained torsional shear to triaxial compression did not change the pattern of behavior observed in the hollow cylinder tests. The angular sand showed a stable response to shearing, contrary to rounded sand, which showed a significant reduction in strength after transient peak strength. The sample preparation method can affect the initial fabric anisotropy of sand. Miura and Toki [20] suggested that the pluviation method creates the most significant anisotropy, and rod plunging approximates an isotropic fabric. However, no comprehensive study has compared the influence of different methods of specimen preparation on the anisotropic behavior of sand.

In this study, the effects of initial stress conditions and the sample preparation method on the anisotropic behavior of sand are investigated. The tests are performed under a drained condition on isotropic- and anisotropic-consolidated sandy specimens that are prepared by air pluviation and wet tamping approaches. Several hollow cylinder tests with different directions of principal stresses during the consolidation and loading phases are performed, and the effect of the initial rotation of principal stresses during consolidation on the anisotropic behavior of medium dense sand is observed.

2. Test apparatus, material properties, and sample preparation

2.1. Test apparatus

The Hollow Cylindrical Apparatus (HCA) is a valuable tool for studying the behavior of sand under inclined

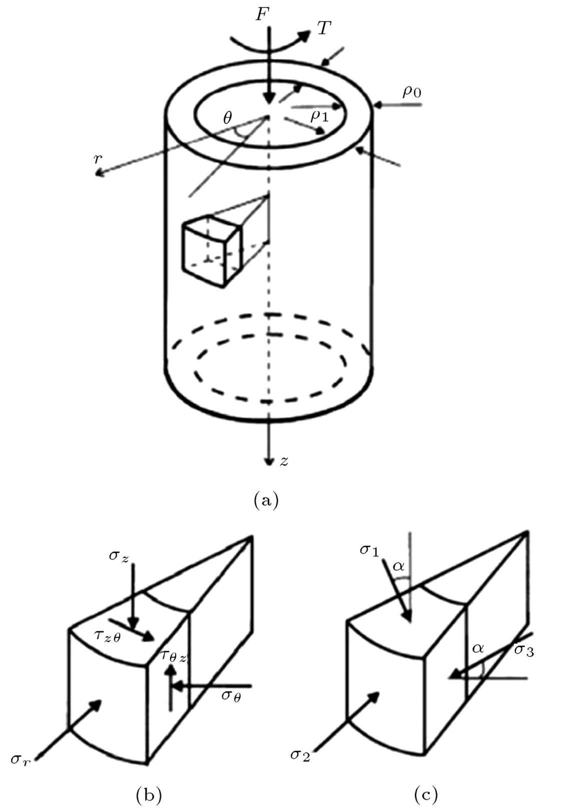

Figure 2. Idealized stress and strain components within HCA subjected to axial and torsional loads: (a) Hollow cylinder coordinates; (b) element component stresses; and (c) element principal stresses (Cai 2010) [11].

principal stresses. The HCA allows the independent control of the magnitudes of the principal stresses and the rotation of the major-minor principal stress axes, while the specimen deformational responses are recorded. In this study, the HCA of the Iran University of Science and Technology (IUST) is used. Axial and rotational loads are applied using two separate electrical motors and drives. The cell, back and inner pressures are controlled and measured by Digital Pressure-Volume Controllers (DPVC) for the precise regulation and measurement of the liquid pressure.

The state of stress in a hollow cylinder test is defined with reference to cylindrical coordinates, in terms of the stress components shown in Figure 2. The stresses and strains are not ideally uniform across the section of the hollow cylindrical specimen through axis r in cylindrical coordinates for various loading conditions. Therefore, to consider the hollow cylinder an element, average values are calculated based on the relations derived by Hight et al. [21].

2.2. Material properties

All tests were performed on Firoozkuh sand passed through a no. 16 sieve (sieve opening = 1.18 mm). Bahadori et al. [22] studied the undrained anisotropy of this type of sand using a hollow cylinder apparatus.

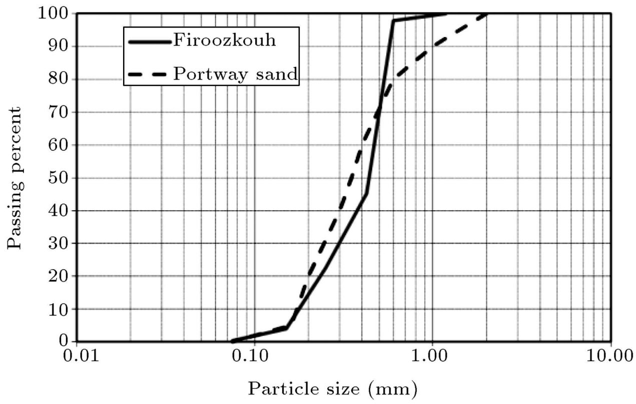

Figure 3. Particle size distribution of Firoozkuh sand and Portway sand.

Figure 4. Microscopic photo of Firoozkouh sand.

The specific gravity is 2.658, the coefficient of uniformity is 2.75, and the maximum and minimum void ratios are 0.913 and 0.568, respectively. A comparison of the particle size distributions of Firoozkuh sand and Portway sand are presented in Figure 3. The shape of the sand particles is shown in Figure 4.

2.3. Specimen preparation

All specimens were prepared with a height of 200 mm and outer and inner diameters of 100 and 60 mm, respectively. Two different methods were applied to prepare the specimens with different fabrics. Most specimens were prepared by air pluviation through a 0.5 m long tube with a diameter of 0.5 cm. The tip of the tube was maintained at 20 cm above the sand surface during deposition in order to obtain the medium dense specimens. A pre-weighed amount of dry sand was pluviated into the specimen cavity, which generated specimens of medium dense sand with void ratios of 0.747-0.757, corresponding to a relative density of 45-48%.

Other specimens were prepared by the wet tamping method. To achieve uniform density at the top and bottom of each layer, compaction was performed using a procedure explained by Ladd [23]. Each layer was

Table 1. Summary of test conditions for drained hollow torsion tests.

Test no.	Code	e_0	σ'_{mc} (kPa)	b	$\delta\alpha$	R_c	α_c
1	I-$\delta\alpha$0	0.748	200	0	0	1	-
2	I-$\delta\alpha$15	0.731	200	0	15	1	-
3	I-$\delta\alpha$30	0.737	200	0	30	1	-
4	I-$\delta\alpha$45	0.738	200	0	45	1	-
5	A0-$\delta\alpha$0	0.748	200	0	0	2	0
6	A0-$\delta\alpha$15	0.744	200	0	15	2	0
7	A0-$\delta\alpha$30	0.710	200	0	30	2	0
8	A0-$\delta\alpha$45	0.733	200	0	45	2	0
9	A45-$\delta\alpha$0	0.747	200	0	0	2	45
10	A45-$\delta\alpha$15	0.735	200	0	15	2	45
11	A45-$\delta\alpha$30	0.746	200	0	30	2	45
12	A45-$\delta\alpha$45	0.724	200	0	45	2	45
13	C-A0-$\delta\alpha$0	0.731	200	0	0	2	0
14	C-A0-$\delta\alpha$15	0.729	200	0	15	2	0
15	C-A0-$\delta\alpha$30	0.733	200	0	30	2	0
16	C-A0-$\delta\alpha$45	0.730	200	0	45	2	0
17	C-I-$\delta\alpha$0	0.733	200	0	0	1	-
18	C-I-$\delta\alpha$15	0.729	200	0	15	1	-
19	C-I-$\delta\alpha$30	0.736	200	0	30	1	-
20	C-I-$\delta\alpha$45	0.732	200	0	45	1	-

compacted by a small tamper to achieve the expected thickness.

After placing the pre-weighed sand in a mold, the membranes were attached to the top cap, and a small vacuum of 30 kPa was applied to the specimen. After detaching the inner mold segments, the specimen was installed on the loading apparatus, the outer mold was removed, and the dimensions of the specimen were measured. The vacuum was exchanged with an initial confining pressure of 30 kPa. The specimen was saturated by flushing CO_2 and de-aired water. In addition a backpressure of 200 kPa was gradually applied to achieve a high degree of saturation. After saturation to a Skampton's B value greater than 0.96, the specimen was consolidated through the specified stress path.

3. Testing program

Twenty drained torsion shear tests are performed, as shown in Table 1. All specimens are consolidated under constant mean effective stress (σ'_m) equal to 200 kPa through the different stress paths. The specimens are sheared through the same stress path used in the conventional drained triaxial test ($\Delta q/\Delta\sigma'_m = 3$). The principal stresses are rotated in different tests. The principal stresses, σ_2 and σ_3, are the same. Hence, the mean stress ratio, b, is equal to 0 during the loading phase. It should be mentioned that in specimens consolidated under inclined principal stresses (α_c = 45), the parameter, b, is not constant during shearing and gradually decreases from $b = \sin^2 \alpha_c$ to $b = 0$.

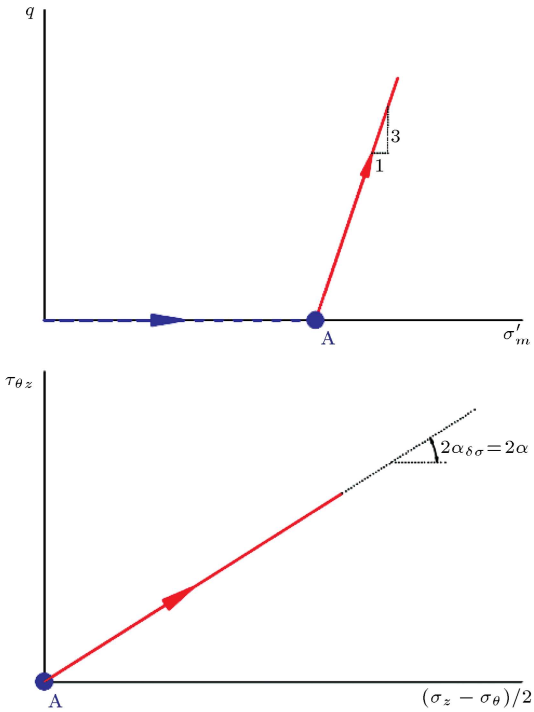

Figure 5. Stress path used in tests series I.

3.1. *Test series I*

Four isotropic tests, series I, are consolidated under an isotropic condition. The stress path used in these tests is shown in Figure 5 as $q - \sigma'_m$ and $\tau_{\theta z} - (\sigma_z - \sigma_\theta)/2$ spaces. In these tests, during consolidation, the principal stresses are simultaneously increased to 200 kPa, and the principal stress ratio, R_c, defined as Eq. (1), is controlled to be constant, equal to unity. The specimens are sheared under different inclinations of principal stress increments, $\alpha_{\delta\sigma}$, defined as Eq. (2), varying from zero to 45°. The parameters, $\delta\tau_{\theta z}$, $\delta\sigma_z$ and $\delta\sigma_\theta$, in Eq. (1) are the increments of $\tau_{\theta z}$, σ_z and σ_θ, respectively. In test series I, the direction of principal stress increments, $\alpha_{\delta\sigma}$, and principal stress, α, are the same value.

$$R_c = \frac{\sigma'_{1c}}{\sigma'_{3c}}, \tag{1}$$

$$\tan 2\alpha_{\delta\sigma} = \frac{2\delta\tau_{\theta z}}{\delta\sigma_z - \delta\sigma_\theta}. \tag{2}$$

3.2. *Test series A0*

In the anisotropic test series A0, four tests are carried out on specimens consolidated under an anisotropic stress condition. The stress path used in these tests is

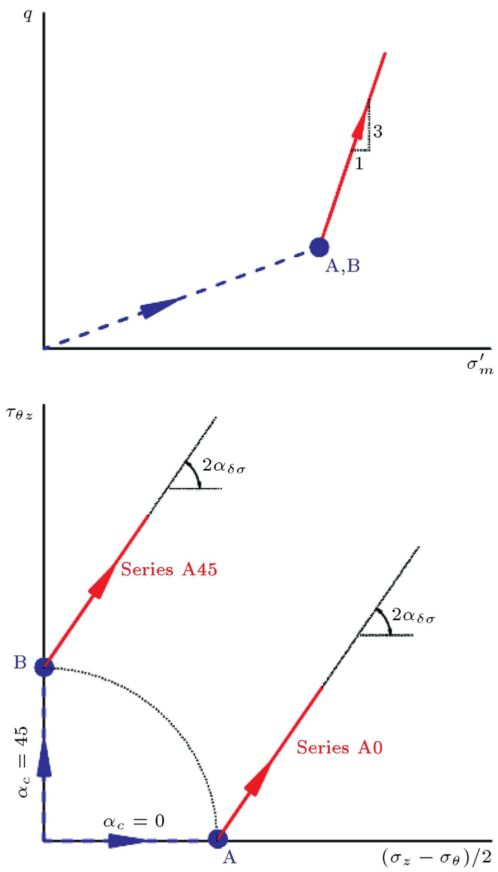

Figure 6. Stress path used in tests series A0 and A45.

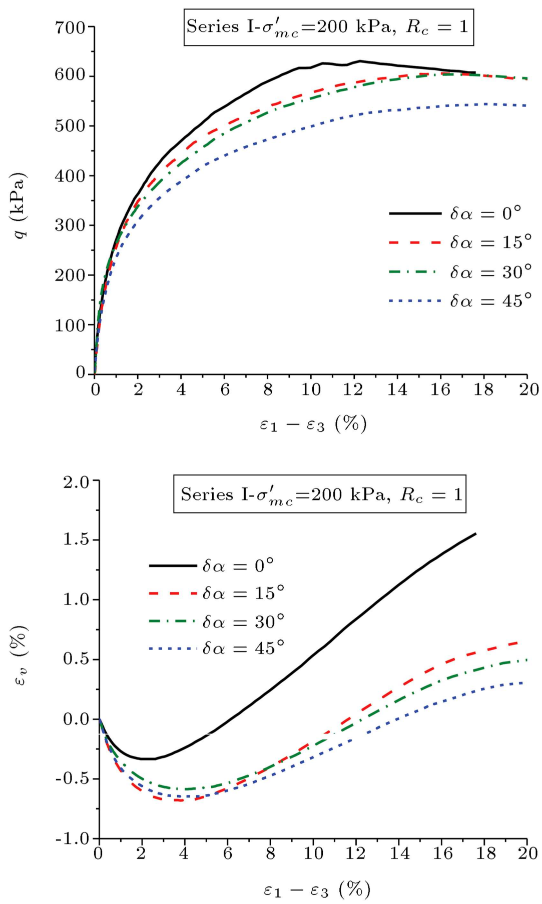

Figure 7. Anisotropy in stress-strain and deformation of isotropic consolidated sand prepared by air pluviation method (series I).

shown in Figure 6. Specimens are consolidated under an anisotropic condition in which the major principal stress is applied perpendicular to the bedding plane ($\alpha_c = 0$) and the principal stress ratio is held constant ($R_c = 2$). The specimens are sheared under different inclinations of principal stress increments, $\alpha_{\delta\sigma}$, varying from zero to 45°. In the test series A0, the direction of principal stress increments, $\alpha_{\delta\sigma}$, is not equal to the direction of the principal stress, α ($\alpha_{\delta\sigma} < \alpha$ for $\alpha_c = 0$ and $\alpha_{\delta\sigma} > \alpha$ for $\alpha_c = 45$).

3.3. Test series A45

In order to study the effect of the inclination of the principal stress during consolidation, α_c, on the anisotropic behavior of sand, four tests (series A45) are performed on inclined consolidated specimens. The stress path used in these tests is illustrated in Figure 6. During the consolidation phase, the rotation of principal stresses has been set to a constant value of $\alpha_c = 45°$.

3.4. Test series C

Similar to test series I and A0, test series C is performed in two categories, C-I and C-A0. However, the specimens are prepared using the wet tamping method in order to investigate the influence of the fabric on the anisotropic behavior of sand.

4. Test results

Figure 7 shows the response of Firoozkuh sand consolidated under isotropic condition (series I) and sheared with $b = 0$ and $\alpha_{\delta\sigma}$ ranging from 0° to 45° in the different tests. The strength of sand decreased as $\alpha_{\delta\sigma}$ increased. Medium dense sand, shearing with $\alpha_{\delta\sigma} = 0$, showed noticeably dilative behavior after an initial contraction in small strains ($\varepsilon_1 - \varepsilon_3 < 2\%$). The dilative behavior of the sand decreased obviously as $\alpha_{\delta\sigma}$ increased. Similar behavior (Figure 8) was reported by Cai [11].

The behavior of Firoozkuh sand, prepared by the wet tamping method (series C-I), is shown in Figure 9. The figure shows that specimens prepared by the wet tamping method displayed obviously brittle behavior during shearing. The modulus of specimens prepared by wet tamping was more than the modulus of the specimens prepared by air pluviation in the range of a small strain. However, for strains more than 2%, the deformation of these specimens increased abruptly, and the failure strength of the wet-tamped specimens was less than that of the air pluviated specimens.

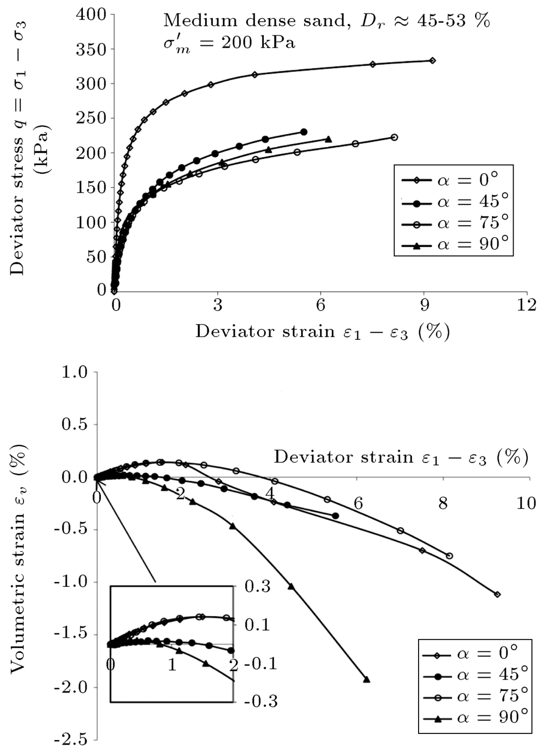

Figure 8. Variation of deviator stress and volumetric strain versus shear strain (Cai 2010) [11].

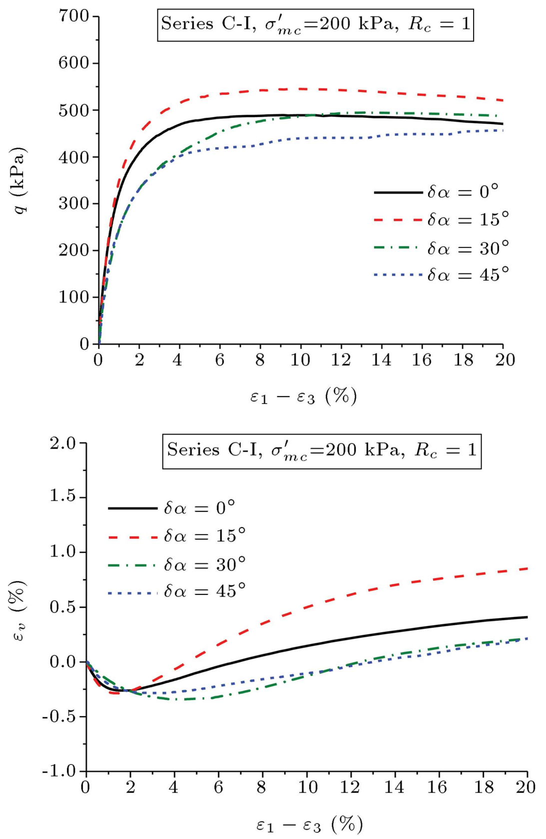

Figure 9. Anisotropy in stress-strain and deformation of isotropic consolidated sand prepared by wet tamping method (series C-I).

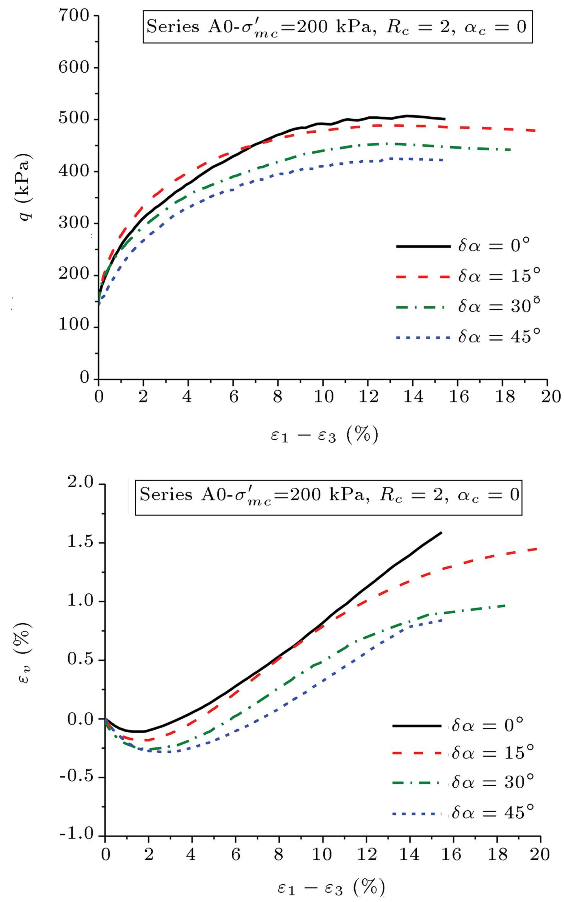

Figure 10. Anisotropy in stress-strain and deformation of anisotropic consolidated sand ($\alpha_c = 0$) prepared by air pluviation method (series A0).

The behavior of Firoozkuh sand, series A-0, consolidated to identical σ'_{mc} = 200 kPa, in anisotropic condition (R_c = 2), with the vertical direction of principal stresses during consolidation (α_c = 0) is illustrated in Figure 10. The same tests were performed on the specimens prepared by the wet tamping method. The results are shown in Figure 11.

The behavior of sand subjected to inclined stress during consolidation (series A45) is illustrated in Figure 12. In addition, a comprehensive analysis and implication of test results is presented and the influence of fabric and initial stresses on the different parameters of sand is evaluated.

4.1. Influence of initial stress state on the behavior of sand

The comparison of the results of test series I and A0 showed that the behavior of the sand was dramatically influenced by the initial stress state. As Figure 13 indicates, for $\alpha_{\delta\sigma}$ = 0, the specimens consolidated under anisotropic initial stresses with R_c = 2 and α_c = 0 showed softer behavior than the isotropic consolidated specimens (R_c = 1). Moreover, the shear strength of specimens, consolidated with R_c = 2

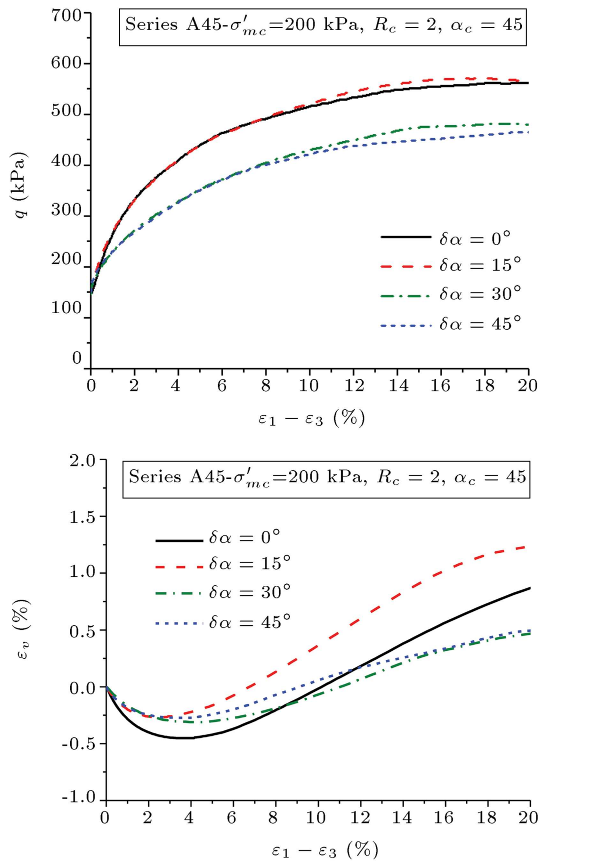

Figure 11. Anisotropy in stress-strain and deformation of anisotropic consolidated sand ($\alpha_c = 45$) prepared by air pluviation method (series A45).

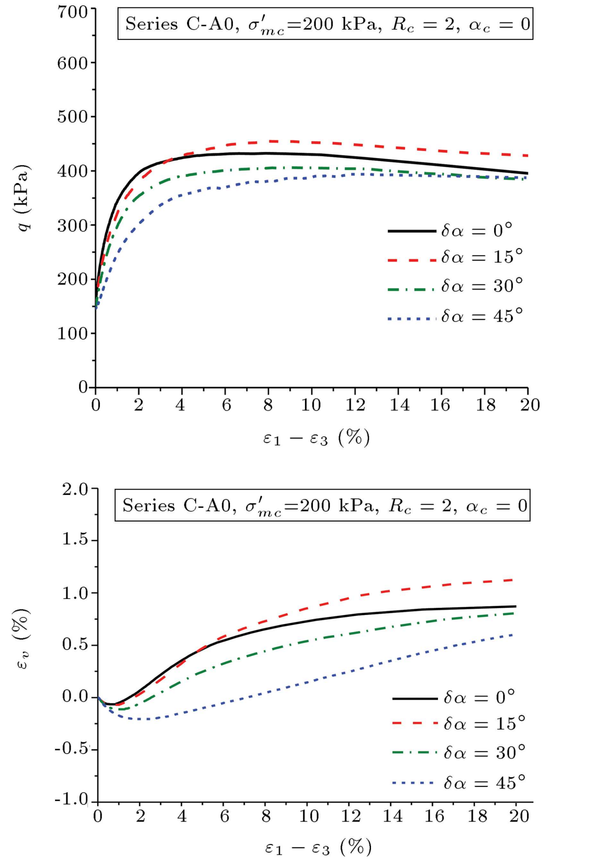

Figure 12. Anisotropy in stress-strain and deformation of anisotropic consolidated sand ($\alpha_c = 0$) prepared by wet tamping method (series C-A0).

and $\alpha_c = 0$, was less than that of the isotropically consolidated specimens.

Regarding the $\varepsilon_v - (\varepsilon_1 - \varepsilon_3)$ graphs, the specimens consolidated under anisotropic stresses showed more dilative behavior than specimens consolidated under isotropic stresses. It seems that the dilative behavior of sand was strongly influenced by the initial stress condition. In fact, the initial deviator stress produces an initial shear strain in soil, which may change the direction and arrangement of the soil particles, thus, affecting the sand behavior noticeably. Similar results are obtained for specimens sheared with $\alpha_{\delta\sigma} = 0$ (see Figure 14). It is worth noting that the value of initial shear strain is not considered in these figures. However, the value of initial strain is not noticeable and its consideration creates no considerable change in the presentative graphs.

4.2. Anisotropy in shear strength of sand

Figure 15 shows the variations in normalized shear strength at failure point (q_f/σ'_{mc}) versus $\alpha_{\delta\sigma}$ under different conditions of consolidation. The strength of sand depends on the condition of consolidation (R_c and α_c), as well as $\alpha_{\delta\sigma}$. The greater values of shear strength were obtained in isotropic consolidated samples. The results suggest that for test series I and A0, in which the direction of major principal stress during consolidation is aligned with the depositional direction, the shear strength of sand decreased as $\alpha_{\delta\sigma}$ increased. However, in test series A45, the rotation of the principal stress during consolidation changed the particle arrangement and the direction of their contact normal vectors. Hence, in test series A45, the trend of the $q_f - \alpha_{\delta\sigma}$ graph was different from that obtained in test series I and A0. In test series I and A0, the descending gradient of the $q_f - \alpha_{\delta\sigma}$ line increased with $\alpha_{\delta\sigma}$, but, in test series A45, the gradient of the variation line decreased for $\alpha_{\delta\sigma} > 30°$. Thus, the shear strength of the soil under inclined loads with $\alpha_{\delta\sigma} = 45$ was close to the value of the shear strength at the inclined loading test with $\alpha_{\delta\sigma} = 30$. Because all specimens were prepared using the same method under controlled constant density, the influence of the inherent anisotropy in each test was the same. The difference between shear strength anisotropy in the different series was noticeable because of the initial induced anisotropy, which was caused by the different conditions of the initial stresses.

In specimens prepared by the wet tamping method (test series C-I and C-A0), maximum strength is observed in $\alpha_{\delta\sigma} = 15°$. The specimens are prepared

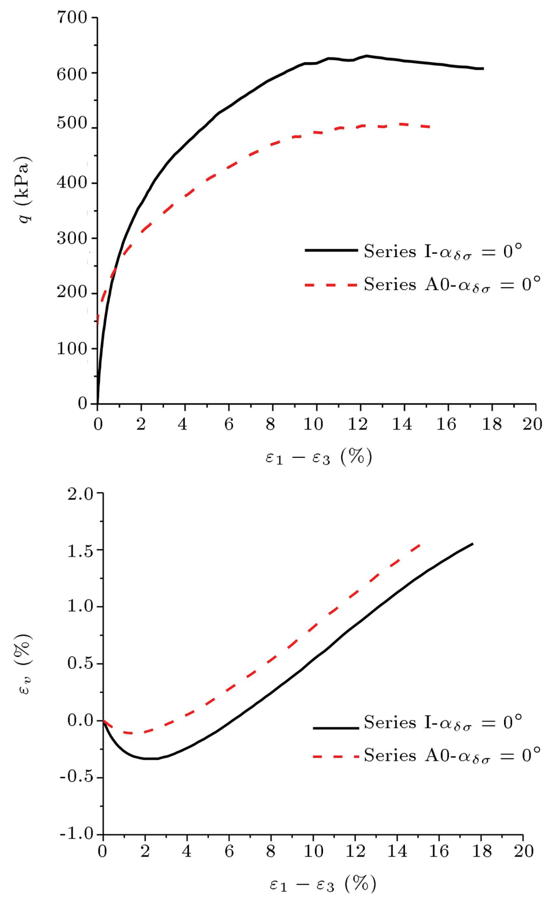

Figure 13. Behavior of isotropic and anisotropic consolidated Firoozkuh sand, sheared with $\alpha_{\delta\sigma} = 0$.

by tamping the wet sand in several layers to obtain homogenous samples, according to the method proposed by Ladd (1978) [23]. However, the boundary between two layers may be a potentially weak zone, which may affect the strength of the soil if the failure surface coincides with these weak zones. As noted earlier in this study, the stress is similar to the conventional triaxial test with the controlling parameter b equal to zero. Hence, in tests with $\alpha_{\delta\sigma} = 0$, the $\sigma_1 - \sigma_3$ plane may have rotated from $z-\theta$ to $z-r$. Consequently, the failure surface developed along the radial direction (r) instead of the tangential direction (θ). Therefore, the failure surface developed along the weak zones near the boundaries of the compacted layers at the center of the specimen. Thus, the results indicated that the behavior of wet-tamped specimens sheared with $\alpha_{\delta\sigma} = 0$ differs from others, because the failure plane is switched from $z-\theta$ to the $z-r$ plane.

The variation in the friction angle, ϕ', with the value of α is presented in Figure 16. The parameter, ϕ', is determined as follows:

$$\sin\phi' = \frac{2\tau_{\theta z(f)}}{\sigma_{1(f)} - \sigma_{3(f)}}, \tag{3}$$

where $\tau_{\theta z(f)}$, $\sigma_{1(f)}$ and $\sigma_{3(f)}$ are rotational shear stress and maximum and minimum principal stresses at the failure point, respectively. The effective friction angle ranges from 35° to 36° in the isotropic consolidated samples, 33.5° to 35° in the vertical anisotropic consolidated samples, and 34.5° to 36° in the inclined anisotropic consolidated samples. The results showed that the variation of ϕ' in the range of 1.0 – 1.5° was caused by the rotation of the principal stress from 0° to 45°. Thus, in medium dense Firoozkuh sand consolidated under different conditions, the initial stress condition of the sand did not have a noticeable effect on the parameter, ϕ'. The same results were obtained in the specimens prepared by the wet tamping method.

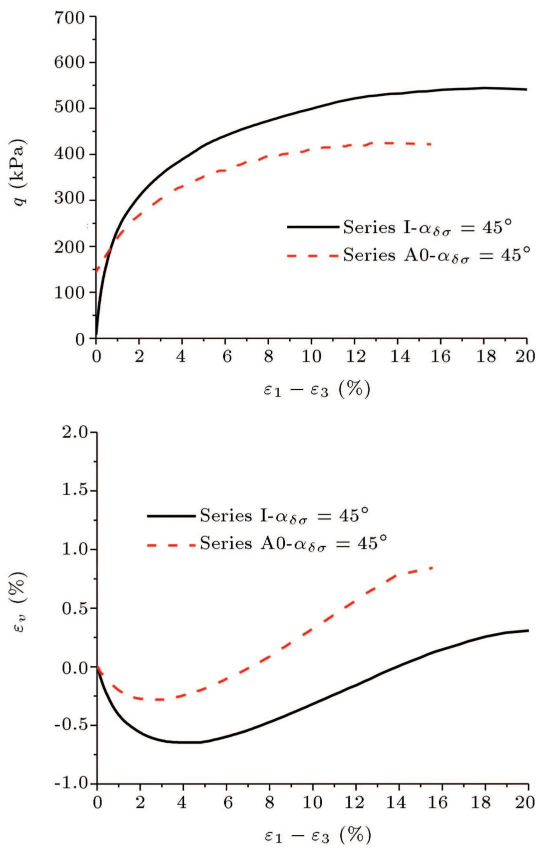

Figure 14. Behavior of isotropic and anisotropic consolidated Firoozkuh sand, sheared with $\alpha_{\delta\sigma} = 45$.

4.3. Anisotropy in secant shear modulus of Firoozkuh sand

Shear modulus is an important parameter in predicting the deformation of soil in geotechnical problems. In practice, it is necessary to estimate the soil modulus in the range of the usual strains that occur under service loads. Figures 17 and 18 present the stress-strain behavior of sand in relatively small shear strains. As these figures show, the modulus of medium-dense Firoozkuh sand consolidated under the isotropic condition is more than the modulus of the anisotropic consolidated sands. Despite the undrained condition,

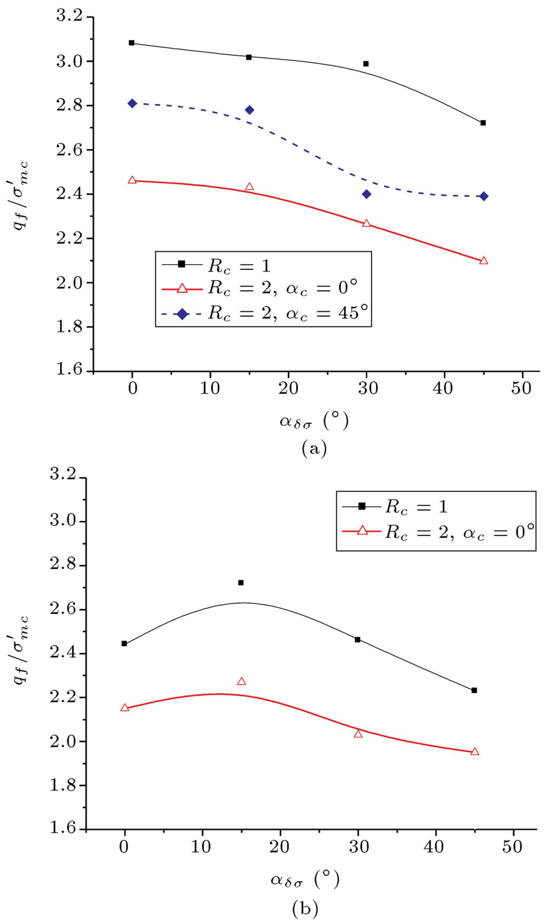

Figure 15. Variation of q/σ'_{mc} at failure point versus α: (a) Prepared by air pluviation method; and (b) prepared by wet tamping method.

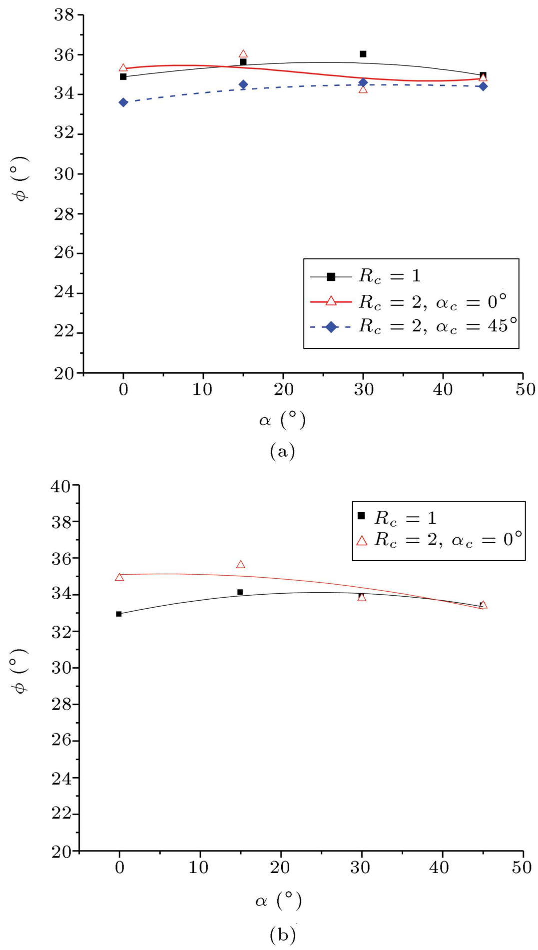

Figure 16. Variation of the effective friction angle ϕ' with the value of α: (a) Prepapred by air pluviation method; and (b) prepared by wet tamping method.

the specimens consolidated under anisotropic stress showed softer behavior under drained conditions. The stress paths, used in test series I and A0 (Figures 5 and 6), are different because of the initial deviator stresses applied in test series A0. This may be the main cause of decreasing the shear modulus and the shear strength of the sand in test series A0.

The secant modulus of sand under half of the maximum deviator stress (i.e. $0.5q_f$), which is defined as $G_{50} = [q/(\varepsilon_1 - \varepsilon_3)]_{50}$, was used in different tests to study the stress-strain behavior of soil under practical service loads. Variations in the shear modulus of sand, G_{50}, under different conditions of initial stress, are presented in Figures 19 and 20. The figures show that the anisotropy of the sand modulus is influenced by the initial stress state. The shear modulus of medium-dense sand strongly depends on the direction of principal stress. In test series I, the shear modulus of air pluviated sands decreased by less than 13% when $\alpha_{\delta\sigma}$ was changed from 0° to 45°. The curves obtained in test series A0 and A45 showed decreases of 45% and 28%, respectively, in the shear modulus, by changing $\alpha_{\delta\sigma}$ from 0 to 45°. The specimens subjected to vertical anisotropic initial stresses ($\alpha_c = 0$) showed the highest anisotropy in shear modulus, whereas the lowest anisotropy in shear modulus was observed in the isotropic consolidated specimens. The soil fabric also affected the shear modulus anisotropy of the sand. As Figure 20 shows, a decrease of 66% in the shear modulus of wet tamped sands subjected to vertical anisotropic initial stresses (test series C-I) was observed by changing $\alpha_{\delta\sigma}$ from 0 to 45°, whereas lower anisotropy in the shear modulus (decreased about 24% by changing $\alpha_{\delta\sigma}$ from 0 to 45°) was observed in isotropic consolidated wet tamped specimens. The obtained results show that the anisotropy in the soil modulus of sands was noticeably influenced by varying the soil fabric from air pluviation to wet tamping.

5. Conclusion

Both the initial stress state and the soil fabric had noticeable effects on the drained behavior of the sand specimens. This was investigated in Firoozkuh sand with $D_r = 45 - 48\%$ under multiaxial loading. The

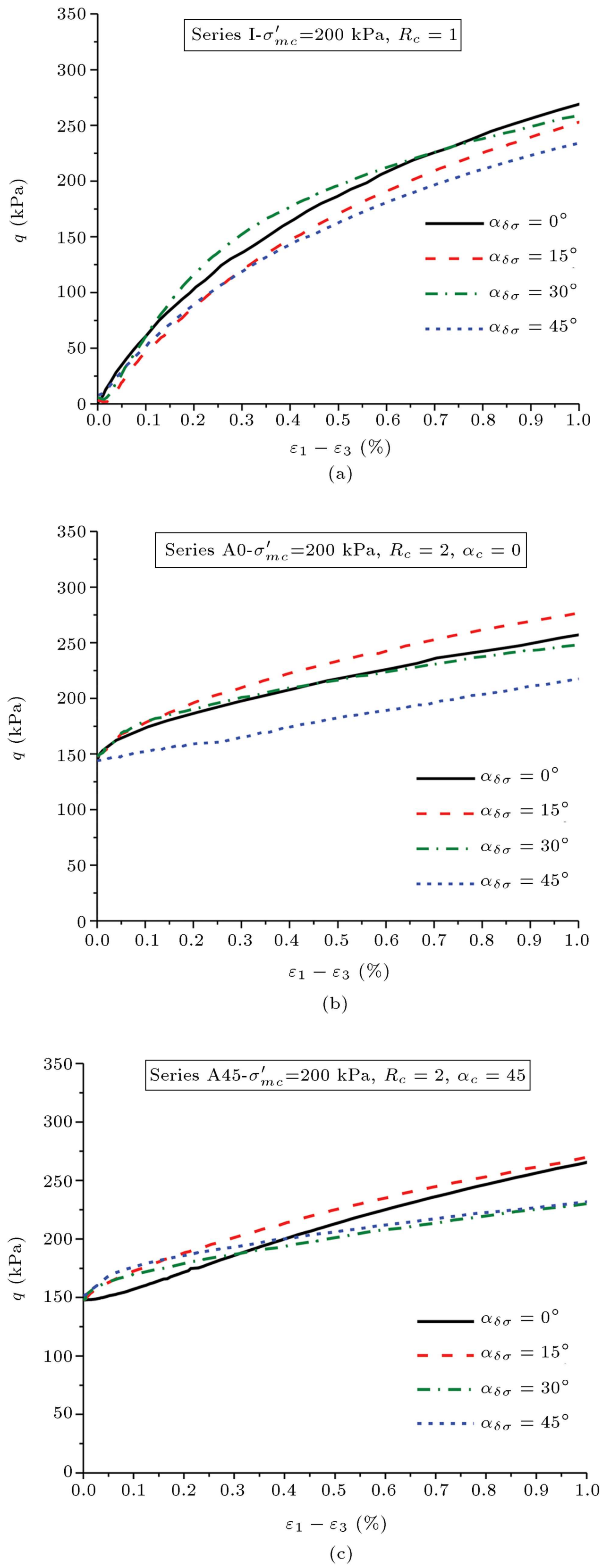

Figure 17. Stress-strain behavior of sand prepared by air pluviation method: (a) Isotropic consolidation; (b) vertical anisotropic consolidation; and (c) inclined anisotropic consolidation with $\alpha_c = 45°$.

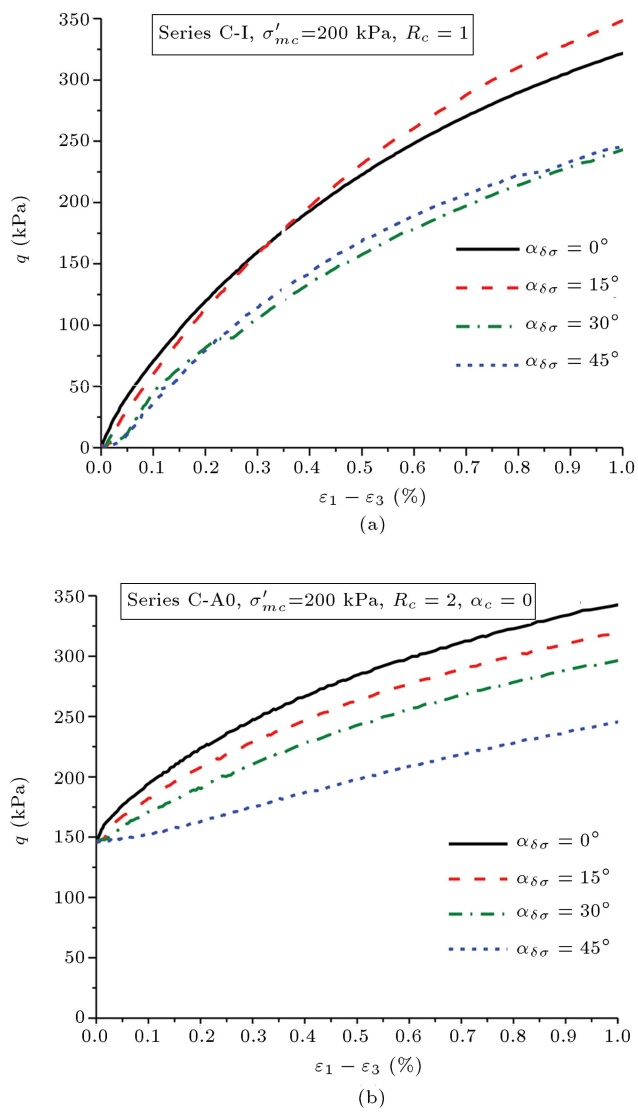

Figure 18. Stress-strain behavior of sand prepared by wet tamping method: (a) Isotropic consolidation; (b) vertical anisotropic consolidation; and (c) inclined anisotropic consolidation with $\alpha_c = 45°$.

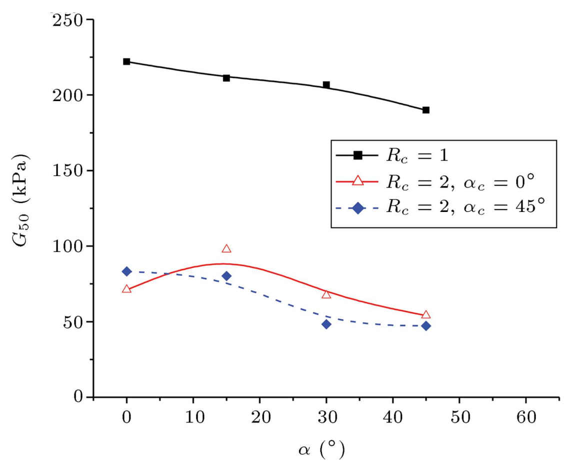

Figure 19. Variation of soil modulus versus α prepared by air pluviation method.

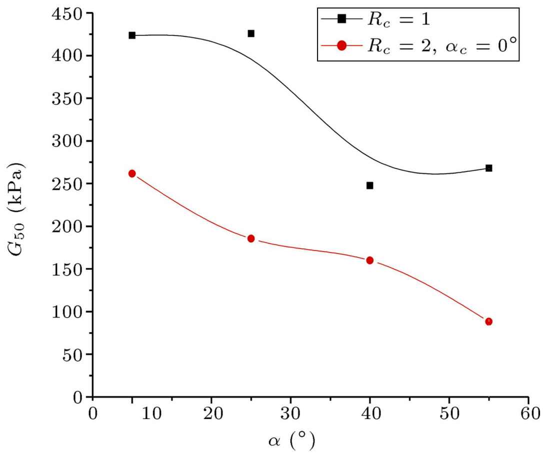

Figure 20. Variation of soil modulus versus α prepared by wet tamping method (series C-I and C-A0).

specimens were sheared under a variety of stress paths in different principal stress directions. The main conclusions of the current study are as follows:

- The shear strength of the tested sand under the drained condition decreased by increasing the inclination of principal stress increments, with respect to the depositional direction ($\alpha_{\delta\sigma}$). The volumetric strain of air pluviated Firoozkuh sand may transform from dilative to contractive behavior by increasing $\alpha_{\delta\sigma}$.
- The volumetric strain of sand may be strongly influenced by initial stress conditions. Sand specimens consolidated under anisotropic stresses ($R_c = 2$) showed more dilative behavior than specimens consolidated under isotropic stresses. In anisotropic consolidated specimens, the initial shear strain in the soil, because of initial deviator stress, may change the direction and arrangement of the soil particles, subsequently having a noticeable effect on the behavior of the sand.
- The inclination of principal stresses during consolidation (α_c) affected the anisotropic behavior of sand specimens. The curves, $G_{50}-\alpha_{\delta\sigma}$ and $(q_f/\sigma'_m)-\alpha_{\delta\sigma}$, in test series A45 showed a different trend than in test series I and A0. The shear strength of anisotropic consolidated sand relatively increased when the direction of the principal stress increments during shearing ($\alpha_{\delta\sigma}$) was near the direction of principal stresses during consolidation (α_c).
- Regarding the tests conducted in this study, a variation of $\alpha_{\delta\sigma}$ in the range of 0° to 45° may cause a decrease of more than 50% in the shear modulus of sand. The results showed that the shear modulus of sand is dramatically influenced by $\alpha_{\delta\sigma}$. Hence, the anisotropy in the stress-strain behavior of sand should be emphasized in both research and geotechnical design.
- The initial stress state had a significant effect on the stress-strain behavior of the sand specimens, particularly in practical strains. In anisotropic consolidated sand, the anisotropy observed in the soil modulus may be three times more than the anisotropy observed in isotropic-consolidated sands.
- The sample preparation method (soil fabric) had a major effect on the stress-strain-strength behavior of the medium dense sand specimens. The shear strength of air pluviated sand was greater than that of wet-tamped sand with the same relative density. Moreover, sand prepared by the wet tamping method showed more brittle behavior than air pluviated sands.
- The obtained results show that the anisotropy in the shear modulus of sand may increase to 200% by changing the soil fabric from air pluviation to wet tamping. Hence, the anisotropy in the shear modulus of Firoozkuh sand is strongly influenced by changing soil fabric, as well as initial stress state. Significantly, no important difference was observed in the anisotropy of the shear strength of Firoozkuh sand by varying the soil fabric.

References

1. Wijewickereme, D. and Vaid, Y.P. "Experimental observation on the response of loose sand under simultaneous increase in stress ratio and rotation of principal stresses", *Canadian Geotechnical Journal*, **45**, pp. 597-610 (2008).
2. Lade, P.V., Nam, J. and Hong, Y.P. "Shear banding and cross-anisotropic behavior observed in laboratory sand tests with stress rotation", *Canadian Geotechnical Journal*, **45**(1), pp. 74-84 (2008).
3. Kumruzzaman, M.D. and Yin, J.H. "Influence of principal stress direction on the stress-strain behavior of completely decomposed granite", *Facta Universitatis-Architecture and Civil Engineering*, **8**(1), pp. 79-97 (2010).
4. Yu, H.S., Li, X. and Cai, Y. "Sand behavior under principal stress rotation: Observation and modeling", *Multiscale and Multiphysics Processes in Geomechanics*, pp. 25-28 (2011).
5. Doanh, T., Dubujet, P.H. and Protiere, X. "On the undrained strain-induced anisotropy of loose sand", *Acta Geotechnica*, **8**(3), pp. 293-309 (2013).
6. Lade, P.V. "Shear banding in cross-anisotropic sand tests with stress rotation", *Advances in Bifurcation and Degradation in Geomaterials*, **11**, pp. 285-291 (2011).
7. Symes, M.J., Gens, A. and Hight, D.W. "Drained principal stress rotation in saturated sand", *Geotechnique*, **38**(1), pp. 59-81 (1988).
8. Wong, R.K.S. and Arthur, J.R.F. "Induced and inherent anisotropy in sand", *Geotechnique*, **35**(4), pp. 471-481 (1985).

9. Arthur, J.R.F. and Assadi, A. "Ruptured sand sheared in plane strain", *9th Int. Conf. of Soil Mech. and Found. Engrg.*, **1**, Tokyo, Japan, pp. 19-22 (1977).
10. Oda, M., Koishikawa, I. and Higuchi, T. "Experimental study of anisotropic shear strength of sand by plane strain test", *Soils and Foundations*, **18**(1), pp. 25-38 (1978).
11. Cai, Y. "An experimental study of non-coaxial soil behaviour using hollow cylinder testing", PhD Dissertation, Univ. of Nottingham, UK (2010).
12. Rolo, R. "The anisotropic stress-strain-strength behavior of brittle sediments", PhD Dissertation, Imperial College of Science, UK (2003).
13. Menkiti, C.O. "Behaviour of clayey-sand, with particular reference to principal stress rotation", PhD Dissertation, Imperial College London, UK (1994).
14. Zdravkovic, L. and Jardine, R.J. "Undrained anisotropy of K_0-consolidated silt", *Canadian Geotechnical Journal*, **37**(1), pp. 178-200 (2000).
15. Shibuya, S., Hight, D.W. and Jardine, R.J. "Local boundary surface of a loose sand dependent on consolidation pat", *Soils and Foundations*, **43**(3), pp. 85-93 (2003).
16. Foundoukos, M. "Investigation of soil anisotropy using a hollow cylinder apparatus and numerical analysis", PhD Dissertation, Imperial College London, UK (2005).
17. Sivathayalan, S. and Vaid, Y.P. "Influence of generalized initial state and principal stress rotation on the undrained response of sands", *Canadian Geotechnical Journal*, **39**(1), pp. 63-67 (2002).
18. Nishimura, S. "Laboratory study on anisotropy of natural London clay", PhD Dissertation, Imperial College London, UK (2005).
19. Tsomokos, A. and Georgiannou, V.N. "Effect of grain shape and angularity on the undrained response of fine sands", *Canadian Geotechnical Journal*, **47**(5), pp. 539-551 (2010).
20. Miura, S. and Toki, S. "Anisotropy in mechanical properties and its simulation of sands sampled from natural deposits", *Soils and Foundations*, **24**(3), pp. 69-84 (1984).
21. Hight, D.W., Genes, A. and Symes, M.J. "The development of new hollow cylinder apparatus for investigating the effects of principal stress rotation in soils", *Geotechnique*, **33**(4), pp. 355-383 (1983).
22. Bahadori, H., Ghalandarzadeh, A. and Towhata, I. "Effect of non-plastic silt on anisotropic behavior of sand", *Soil and Foundations*, **48**(4), pp. 531-545 (2008).
23. Ladd, R.S. "Preparing test specimens using undercompaction", *Geotechnical Testing Journal*, **1**(1), pp. 16-23 (1978).

Biographies

Hamid Reza Razeghi received his PhD degree from Tohoku University, Japan, in 2000, and is now Associate Professor in the School of Civil Engineering at the Iran University of Science and Technology, Iran. His research interests include geotechnical and geoenvironmental engineering.

Hadi Mohamadzadeh received his MS degree in Geotechnical Engineering from Tehran University, Iran, in 2008, and is now a PhD degree candidate in the School of Civil Engineering at the Iran University of Science and Technology, Iran. His research interests include experimental geotechnics, particularly in element testing, three-dimensional analysis of reinforced slopes and geostatistical analysis in site investigation.