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# Effects of Anisotropic Consolidation and Stress Reversal on the Liquefaction Resistance of Sands and Silty Sands

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**ABSTRACT:** In this study, a total number of 83 undrained cyclic tests were carried out on Firoozkuh pure sand and sand-silt mixtures using cyclic triaxial apparatus. The tested specimens were subjected to both isotropic and anisotropic consolidation. The anisotropic consolidation was applied both in compression and in extension modes. The results indicate that the isotropic consolidated pure sandy samples when subjected to symmetric cyclic stresses exhibit asymmetric cyclic strains reversely, as extensional part of each cyclic strain curve is larger than compressional part. This behavior of sandy soils could be addressed to the anisotropic behavior of sands. The effect of adding silt on this deformational behavior of sandy specimens is studied too. The results indicated that this behavior disappears in silt mixed sand.

In addition, the effect of anisotropic consolidation on deformational behavior of pure sand and sand-silt mixtures was considered. The results indicate that the cyclic resistance of saturated sand to liquefaction is the function of compressional or extensional consolidation and besides, reversal of cyclic deviator stress. Anisotropic consolidation exerts an initial static deviator stress in triaxial tests. Effect of initial static shear stress on the cyclic liquefaction of sands is acknowledged in the literature and a correction factor of $k_{\square}$ is introduced to take this into account. However, shear stress reversal in the cases with presence of initial static shear stress is another factor that affects the liquefaction potential. A new coefficient called *rc* is introduced in this study to show degree of cyclic stress reversal. Combined effect of initial static shear stress and shear stress reversal is studied and it is shown that the correction factor for initial static shear stress $k_{\square}$ is not sufficient and stress reversal effect should also be considered for correction of cyclic resistance to liquefaction. Effect of initial shear stress and cyclic stress reversal on the silt mixed sands is also studied.

## 1. INTRODUCTION

In the first decades after recognition of liquefaction as the cause for severe damages during Niigata Earthquake (1964), liquefaction related phenomena were thought to be limited to sandy soils. Finer-grained soils were considered less capable of generating high excess pore pressures, which are commonly associated with soil liquefaction. Therefore, most of the previous research work on soil liquefaction had focused on relatively clean sands as it is stated by Yamamuro and Lade (1998). Many natural sandy soils, though, contain a significant amount of fines (passing sieve No. 200, particle size less than 0.074 mm). For this reason the effect of fines content on the liquefaction resistance of soil mixtures has been incorporated in the existing liquefaction susceptibility criteria, Naeini and Baziar (2004). Early investigation from in-situ tests indicate the lower liquefaction susceptibility in the soils with fines and consider the beneficial effect of silt in decreasing the probability of liquefaction of sandy soils, nevertheless many laboratory test thereafter indicate the contrary effect of fines on liquefaction susceptibility of sandy soils as stated by Bouckovalas et al. (2003). Some investigations remark that the major reason for decreasing the resistance to liquefaction of finer-grain soils is related to increasing tendency to contraction of them than soils with sand grain. Yamamuro and Lade (1997b, 1998) and Lade and Yamamuro (1997), through some monotonic tests observed that increasing the non-plastic silt content in Nevada sand increased the volumetric contractive character in both drained and undrained triaxial tests, even when the density was increased.

However, there are many investigations on this subject and different aspects of the issue are studied in recent years. The effect of fine content is determined by introducing new state parameters, Constantine A. Stamatopoulos (2010) and definition of skeleton (intergranular) void ratio and fine (interfine) void ratio in combination of global void ratio of the mixed sand and silt, Athanasopoulos (2003). Further attempts have been made to clarify the effect of fines on the cyclic and monotonic resistance of mixed soils by putting emphasize on the effect of size and shape of fine and host sand, Monkul and Yamamuro (2011).

Another issue that is studied in recent years is the anisotropic behavior of sands. Yoshimine (2000) emphasized the anisotropic behavior of sands by means of monotonic and cyclic triaxial tests and stated that "the undrained cyclic deformation and strength characteristics of sand deposits are significantly affected by the direction of initial shear stress, due to the anisotropy of the specimens. When the initial shear stress was applied in triaxial extension mode, the cyclic strength of the sand was dramatically decreased. In contrast, cyclic strength against liquefaction was greatly increased when the initial shear stress was applied in triaxial compression mode. These findings suggest limitations of triaxial tests as tools for investigating liquefaction of sand under general stress conditions".

Also anisotropic behavior of sands through cyclic tests was noticed by Yoshimine (2000). He showed different mechanical properties of sands in extension and compression modes. However his tests have been done on clean sand and there are not enough data about effect of silt on this type of behavior. Bahadori et al (2008) studied the anisotropic behavior of silt mixed sands.

Hosono and Yoshimine (2008) presented the results of some cyclic triaxial tests in comparison to torsional and simple shear tests.their main achievement was to show that the effect of initial static shear stress in triaxial tetsts is different comparing to those observed in simple shear tests. Although they have attempted to show the effect of principal stress directions and also stress reversal effect on their results, it seems the problem is not clear yet and further investigations are necessary.

The effects of initial state parameters on deformation behavior and liquefaction resistance of sand-silt mixtures are also significant. One of these parameters is anisotropic consolidation which can extremely change the deformation behavior of soils and subsequently change liquefaction resistance of them, Vaid and Sivathayalan (2000). Although the effect of anisotropic consolidation has been studied so far, there is not enough information about its effect on the deformation behavior of sand-silt mixtures especially in extension mode.

Seed and Lee (1969) mentioned two methods for determining liquefaction of isotropic consolidated samples in the tests on sandy soils. The first method remarked that liquefaction happens when the pore water pressure increases and becomes equal to confining pressure and second one (upon the deformation criteria) mentioned that liquefaction happen when double amplitude axial strain rises to 5%. This deformation criterion has been proposed for the isotropic consolidated pure sands and may not be true for pure sands with anisotropic consolidation and also silty soils Hyde et al. (2006).

The objectives of the current paper are (a) to present the results of an experimental investigation of the effect of non-plastic fine contents on reducing the cyclic resistance and on anisotropic behavior of sandy soils. (b) To interpret results obtained from anisotropic consolidated tests on pure sand and silt mixed sand regarding the effect of initial static deviator stress and cyclic shear stress reversal on deformation behavior and subsequently liquefaction potential of pure sand and sand-silt mixtures. Combined effect of initial static shear stress and cyclic stress reversal has main importance in this study.

## 2. MATERIAL PROPERTIES

The Firoozkuh sand and silt are used in the current study. Some of the physical properties of Firoozkuh sand are shown in Table1 and the sand particle size distribution curve is depicted in Figure 1. As it is shown, the sand can be considered as fine sand. The plasticity index of the silt is less than 5 percent and can be addressed as non-PI soil.

Table 1. Physical properties of Firoozkuh sand

| Sand | Gs | $e_{max}$ | $e_{min}$ | D50 (mm) | %FC | Cu | Cc |
|---|---|---|---|---|---|---|---|
| Firoozkuh | 2.65 | 0.874 | 0.548 | 0.27 | 1 | 1.87 | 0.88 |

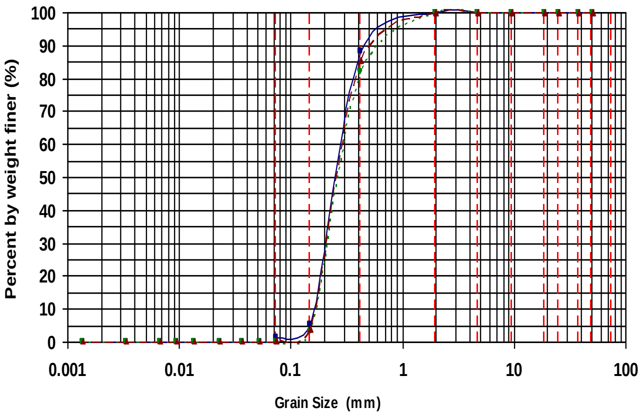



Figure 1 Firoozkuh sand particle size distribution curve

Various silt percentage were added to the sand skeleton. The tested sand-silt mixtures have 15, 30, 50 and 70 percent silt content. The mixture's void ratio decreases till about 35 percent of silt and then increase again in greater silt content. The minimum and maximum void ratio of sand-silt mixtures is depicted in Figure 2.

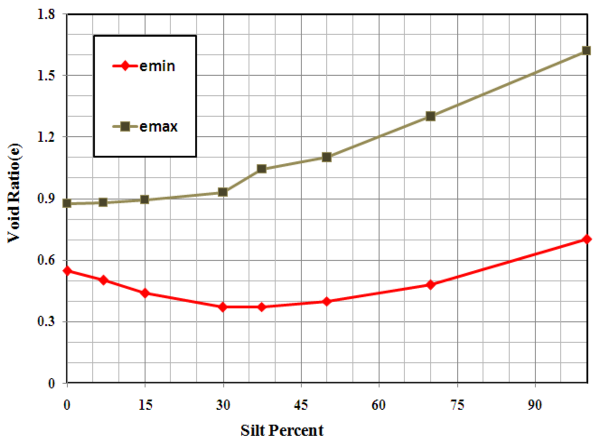



Figure 2. Maximum and minimum void ratio of Firoozkuh sand-silt mixtures

## 3. SAMPLE PREPRATION AND TEST PROCEDURE

The sample preparation methods in this paper are some derivation of dry depositional methods, namely DFD (Dry Funnel Deposition), TFD (Tapped Funnel Deposition), FFD (Fast Funnel Deposition). Specimens prepared using DFD were formed by initially placing the spout of a funnel on the bottom of a split mold. The sand-silt mixtures were placed into the funnel and then it was slowly raised along the specimen axis of symmetry. This allowed the sand to be deposited in a low-energy state without any drop height. This technique is commonly used for testing silty sands. In order to achieve higher densities, the split mold was gently tapped in a symmetrical pattern. This method of creating specimens is referred to as tapped funnel deposition (TFD). Denser specimens also were prepared by raising the funnel more quickly (although still without a drop height) prior to tapping. This reduced the tapping required to achieve a desired density. This technique is referred to as fast funnel deposition (FFD) [10]. After the samples were prepared the saturation stage continued till reaching a value of B=0.95. The consolidation can be performed either isotropic or anisotropic. *K* value can be smaller and larger than unity. Then finally a cyclic deviator stress was applied in both compression and extension side. The frequency was about 0.05 Hz.

## 4. APPARATUS

A cyclic triaxial device was used. The apparatus was modified in such way that enables performing a fully computer controlled stress path. It was possible to apply anisotropic consolidation in both compression and extension way. Cyclic deviator stress could then be controlled to create different amount of stress reversal. The cyclic tests were performed at Soil Dynamics Laboratory of University of Tehran.

## 5. ANISOTROPIC CONSOLIDATION RELEVANT PARAMTERS

The anisotropic consolidation occurs when the effective consolidation stresses have different amounts in horizontal and vertical directions. It is considerable that most of natural soil deposits are consolidated in anisotropic way instead of isotropic one. The parameter for describing anisotropic consolidation is consolidation stress ratio that is defined by the ratio of the lateral stress to axial stress ($K=\sigma'_{cl} / \sigma'_{ca}$). The $\sigma'_{ca}$ and $\sigma'_{cl}$ are axial and lateral consolidation stresses respectively.

In advanced triaxial tests in consolidation stage, it is possible to apply *K* values different than 1.0 that creates anisotropic consolidation. This type of consolidation exerts a sort of induced anisotropy to the soil sample and could affect the behavior of soil during the application of deviator stress. Such effect can be called as induced anisotropy effect. Though the consolidation stress ratio (*K*) is an important parameter for defining the anisotropic consolidation, it is not a comprehensive parameter to study the anisotropy effect particularly in cyclic triaxial tests. The parameter *K* may indicate the presence of static shear stress on the soil body that often is defined by parameter $\alpha$. Parameter $\alpha$ is the ratio of static shear stress to initial confining effective stress. In the current study the effect of *K* or $\alpha$ is investigated on the cyclic behavior of sands and silty sands. However, since the stress reversal is also another important factor that affects the cyclic behavior of soils, combination of anisotropic consolidation and stress reversal are introduced here. For this purpose different types of cyclic stress histories are introduced. These types of stress histories can be created by using different *K* values and cyclic deviator stress amplitudes.

Figure 3 shows the independence of stress reversal from the *K* parameter. At the same *K* (with different applied cyclic deviator stress) the (a) loading pattern has stress reversal, whereas, the (b) one has not stress reversal and as a result, they may cause different behavior in soil specimens.

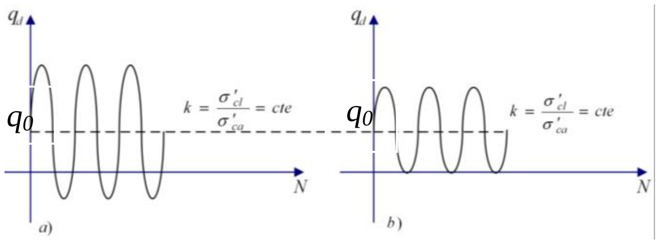



Figure 3. Independence of stress reversal from the value of *K*
a) With stress reversal at the constant *K*
b) Without stress reversal at the constant *K*

In the current study the effect of anisotropic consolidation as well as the effect of stress reversal is studied. Therefore a new parameter that considers the reversal of the cyclic deviator stress in different *K* values is introduced and it is named as reversal coefficient (*rc*). The *rc* is defined as the ratio of the compression domain of cyclic deviator stress to its total compression and extension domain $q_d$ (Figure 4-a). Compression and extension mean $q>0$ and $q<0$ respectively. Cyclic deviator stress $q_d$ is the diameter of Mohr-Coulomb circle and is the maximum shear stress on the plane with orientation of $45^O$ to horizontal plane.

As it can be seen in Figure 4-b, combination of different initial static deviator stress *K* , reversal coefficient *rc* and different $q_d$ values can create different modes of loadings. The following descriptions explain the significance of *rc* values based on Figure 4-b:

$rc>=1$: Cyclic loading with no stress reversal in fully compression mode

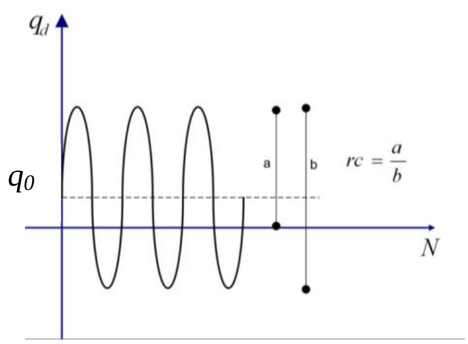
$0.5<rc<1$: Cyclic loading with stress reversal in both compression and extension mode (Dominant compressional loading)

$rc=0.5$: Cyclic loading with stress reversal having equal values in compression and extension modes.

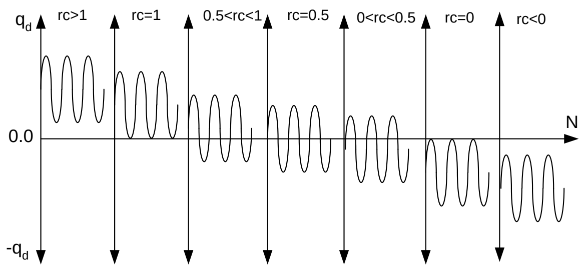
$0<=rc<0.5$: Cyclic loading with stress reversal in both compression and extension mode (Dominant Extensional loading)

rc<0: loading with no stress reversal in fully extensional mode

What is important is that the previously recognized "static shear stress effect", "anisotropic consolidation effect" and "stress reversal effect" could be in the different cyclic loading histories with different *rc* values. This means we can expect to observe different cyclic behavior and probably different liquefaction potential of saturated soils if the cyclic loading takes place with different *rc* values. Using the test results in the coming parts, this issue will be explained in more details.




(a)




(b)

Figure 4. Definition of rc parameter
a- Parameters used in definition of reversal coefficient rc
b- Different rc values in different modes of loading

## 6. RESULTS AND DISCUSSIONS

In this part results of the experimental investigation are presented. Total number of 83 cyclic triaxial tests are conducted on the pure Firoozkuh sand as well as the mixed Firoozkuh sand and silt. Therefore the presented discussion is focused on the behavior of both pure sand and mixed silty sand.

### 6.1 Deformation pattern in cyclic compression and extension modes for isotropic consolidated samples

Typical results of cyclic tests on the saturated pure sand with isotropic consolidation are shown in Figure 5. The reversal coefficient is kept 0.5 during the cyclic loading which indicates that the extensional and compressional deviator stresses are equal during each loading cycle. In other word a symmetric stress history was applied to the soil samples. Although the applied stress was symmetric the axial strain appeared to be asymmetric. Larger deformation takes place in extension side that shows softer behavior in this direction. It could be due to the anisotropic nature of sand. Saturated sand during an undrained triaxial test exhibits different deformation in compression and extension sides. This fact can be observed in Figure 6 too. As it is shown in this figure, progress of axial extensional strain in each cycle is larger than compressional strain. Inherent anisotropy of sand caused by non-uniform particle shapes could be considered as the reason for this type of behavior. Most probably the initial fabric of sand media in all deposition methods makes it to be softer in horizontal direction. As it is shown in Figure 5 the excess pore pressure ratio $ru=\Delta u/P_0'$ has reached 100% at a cycle in that the double apmlitude axial strain ($\varepsilon_{a,DA}$) is almost 5%. Both conditions are commonly assumed as the criteria for onset of liquefaction.

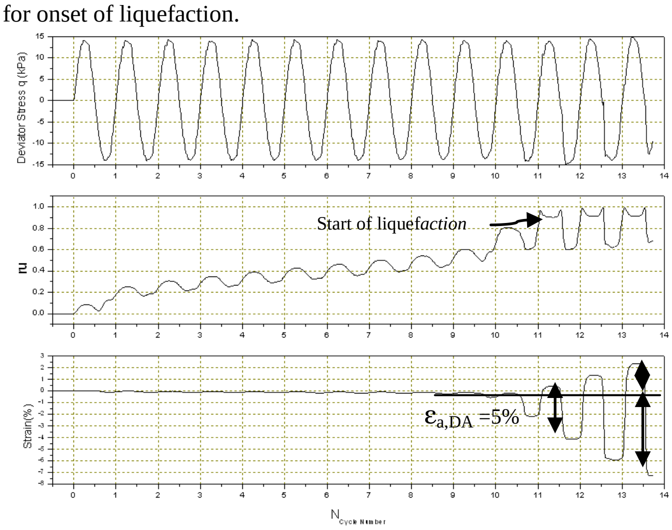



Figure 5 Different compressional and extensional strain during cyclic tests (*P'0*=100kPa, *K*=1, *rc*=0.5, *Dr*=0.55)

### 6.2 Effect of silt content on the cyclic deformation pattern of isotropic consolidated samples

The anisotropic deformation of sands has been noticed in the literature and also was shown for Firoozkuh sand here. In the current study, for realizing the influence of fine particles, some cyclic triaxial tests are carried out on sand-silt mixtures. In these tests $K$ and $rc$ were kept to be 1 and 0.5 respectively indicating the isotropic consolidation and symmetric cyclic stress form. Silt content is selected to be 15%, 30%, 50% and 70% in different tests whereas the relative density was attempted to maintain equal in all tests. The results indicated that deformational anisotropy of sands disappears even with low percentage of fine particle. Figure 7 shows typical stress-strain and stress path curves for the mixture having 15% silt. Although the test is done in isotropic consolidation condition and a symmetric deviator cyclic stress history is applied to the soil sample, the strain history is almost symmetric. The presence of 15% silt has caused almost a isotropic behavior. Figure 8 depicts the strain history of five samples with 0, 15, 30, 50 and 70 percents of silt. According to this figure, with increasing the silt percent to 15% maximum strain has increased significantly indicating a considerable softening. Further increase of silt percent has caused reduction of the maximum cyclic strain. However, adding silt to the host sand has increased the maximum cyclic strain comparing to that of pure sand. Cyclic strain in extension and compression modes are almost equal in all mixed soils that means reduction or disappearance of anisotropy. Disappearance of this kind of anisotropy in sand-silt mixtures can be related to equality of compressional and extensional mechanical properties of them.

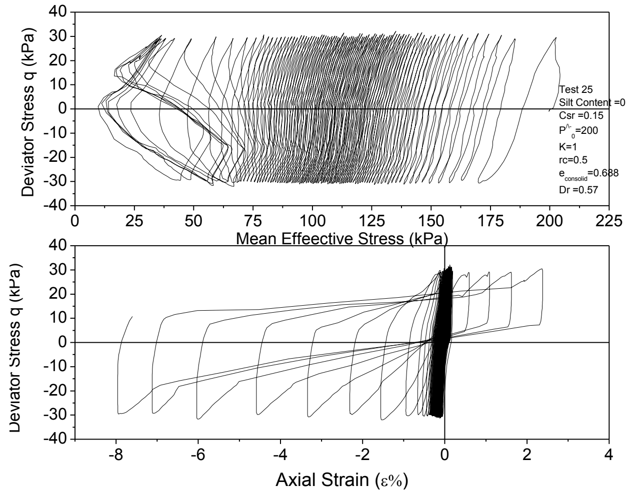



Figure 6 Larger strain in extension side in tests with ($P'_0$=200kPa, $K$=1, $rc$=0.5, $Dr$=0.57)

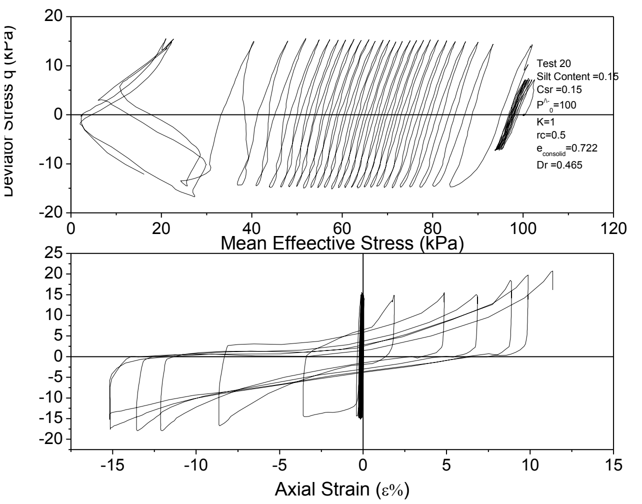



Figure 7 Effect of 15% silt on equating the extensional and compressional strains

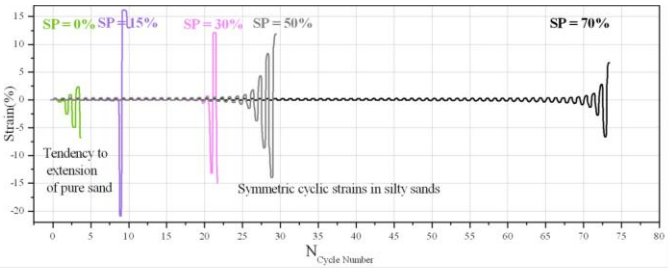



Figure 8 Effect of different silt contents on the axial strains history

Liquefaction potential is also strongly affected by silt content. Figure 9 shows that the cyclic resistance is significantly decreased by adding 15% silt. By increasing silt content the resistance increases gradually but still is lower than that of pure sand. Similar tendency of change in cyclic resistance in different number of cycles is shown in Figure 10. Silt content of 15% has caused the maximum reduction of the cyclic resistance.

### 6.3 Effect of initial static stress and stress reversal on the liquefaction of pure sand

Another series of cyclic triaxial tests on pure Firoozkuh sand has been performed while different anisotropic consolidations together with different degree of deviator stress reversal were applied. In all tests the void ratio and therefore relative density was kept almost constant.

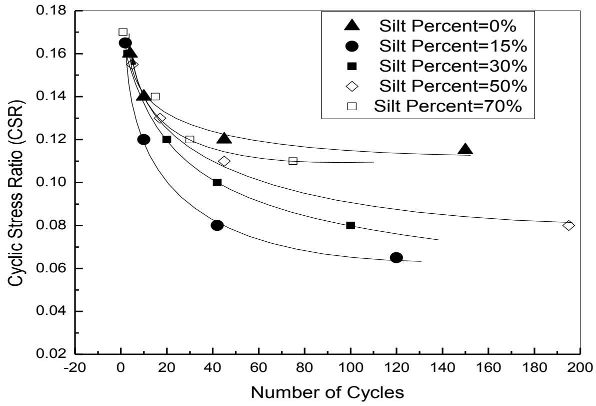



Figure 9 Effect of silt content on the cyclic resistance of Firoozkuh sand to liquefaction

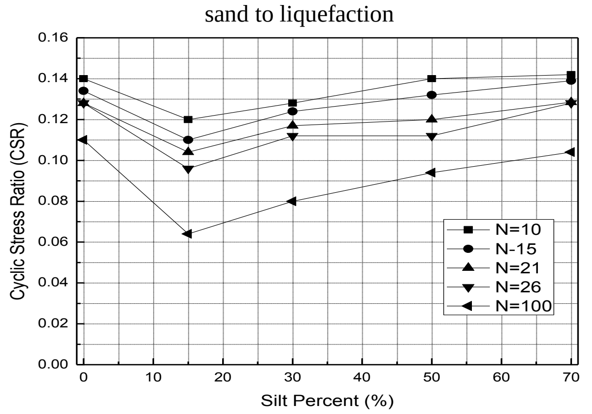



Figure 10 Effect of silt content on the cyclic resistance of Firoozkuh sand in different number of cycles

#### 6.3.1 Compressional consolidation or positive initial static deviator stress

As it is explained before both initial static shear stress and shear stress reversal play important roles in the cyclic resistance to the liquefaction. In cyclic triaxial tests, combination of different initial static stress and stress reversal can be generated. Initial static stress is caused by anisotropic consolidation and stress reversal depends on initial deviator stress and the amplitude of cyclic stress as shown in Figure4. Initial static stress in triaxial test can be defined as $\alpha=q_0/P'_0$. The following equation shows the relation between the "lateral to axial stress ratio" $K$ and $\alpha$:

$$\alpha=\frac{3(1-K)}{2(1+2K)} \tag{1}$$

On the other hand, according to Figure 4-a, reversal coefficient $rc$ can be obtained by the following equation:

$$rc=\frac{q_0+q_d/2}{q_d} \tag{2}$$

where $q_0$ is initial stress and $q_d$ is double amplitude cyclic deviator stress. Rearranging Eq. 2 results in the following equation:

$$rc=\frac{q_0}{q_d}+1/2 \tag{3}$$

Rewriting the Eq. 3 gives the following form for $rc$:

$$rc=\frac{q_0/P'_0}{q_d/P'_0}+1/2 \tag{4}$$

Substituting $q_0/P'_0=\alpha$ and $q_d/P'_0=CSR$ in Eq. 4 gives the following form for $rc$:

$$rc=\frac{\alpha}{CSR}+1/2 \tag{5}$$

When the anisotropic consolidation is under $K$ value less than 1, the $\alpha$ will be positive and is referred to as compressional consolidation here. Figure 11 shows the effect of $K$ (in consolidation stage) and reversal coefficient $rc$ on the cyclic resistance to liquefaction for pure Firoozkuh sand. It is very interesting to notice that in a constant reversal ratio the larger $K$ causes higher resistance to liquefaction. The largest $K$ in this figure is 1.0 that means isotropic consolidation in that the initial static stress $q_0$ is zero. The values less than unity means the initial static stress $q_0$ is higher than zero. As it can be seen in table 2 and Figure 11 the smaller $K$ creates higher initial static deviator stress ratio ($\alpha$) and resistance to liquefaction has increased when the initial static shear stress ratio ($\alpha$) has increased.

On the other hand stress reversal has also important effect on the resistance to liquefaction. As it is explained before the maximum stress reversal happens when $rc$=0.5. Increase in $rc$ from 0.5 to 1 decreases the stress reversal. As clearly is shown in Figure 11 the smallest resistance was when the stress reversal was the maximum. It means larger stress reversal decreases the resistance to liquefaction. Probably the important point here is that the effect of initial static shear stress and cyclic stress reversal could not be separated out and the effect of these factors should be considered in correcting the Cyclic Resistance Ratio ($CRR$) obtained from cyclic triaxial tests. In the existing practice for correction of $CRR$ the coefficient $K_\alpha$ is used without considering the occurrence of stress reversal. Combination of $rc$ and $\alpha$ or $K$ may give appropriate correction when initial static stress is the case for estimation of cyclic resistance to liquefaction. In fact the correction factor for $CRR$ is not only dependent on $K$ or $\alpha$ but is also on reversal coefficient $rc$ and introducing a comprehensive correction factor is necessary.

Figure 12 shows the variations of excess pore pressure and cyclic strain during the tests with different $K$ and $rc$ values. In these tests the relative density was around 50% and the applied cyclic stress in all tests were equal. However, the number of cycles for the excess pore water pressure ratio ($ru$) to reach its maximum value is the largest for the case with $rc$=1 and $K$=0.74. In this condition $\alpha$ is 0.16 and there is no stress reversal and cyclic stress is applied in fully compression state. In contrast the sample with $K$=1 and $rc$=0.5 had the minimum resistance and the maximum $ru$ has occurred faster indicating lower resistance to liquefaction. Interesting observation is that although the resistance to liquefaction for the test in fully compression state is more than other cases, the sample has experienced the larger residual (plastic) strain than other tests.

Table 2 Different anisotropic consolidation, initial static shear stress and stress reversal in the conducted tests

| $K$ | Static stress Ratio ($\alpha$) | Stress reversal coefficient ($rc$) | Loading Mode | Stress reversal |
|---|---|---|---|---|
| 0.48 | 0.40 | 1 | Comp. | No Rev. |
| 0.6 | 0.27 | 1 | Comp. | No Rev. |
| 0.74 | 0.16 | 1 | Comp. | No Rev. |
| 0.86 | 0.08 | 0.75 | Comp.- Ext. | Rev. |
| 0.77 | 0.14 | 0.75 | Comp.-Ext. | Rev. |
| 0.67 | 0.21 | 0.75 | Comp.-Ext. | Rev. |
| 1 | 0 | 0.5 | Comp.-Ext. | Rev. |

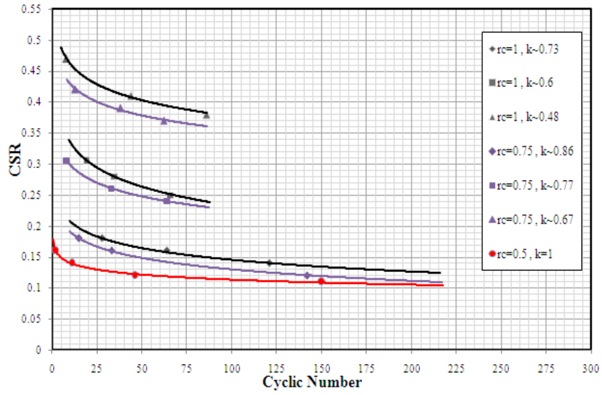



Figure 11 Effect of rc and K on a) excess pore water pressure and b) deformational behavior of compression consolidated sandy specimens

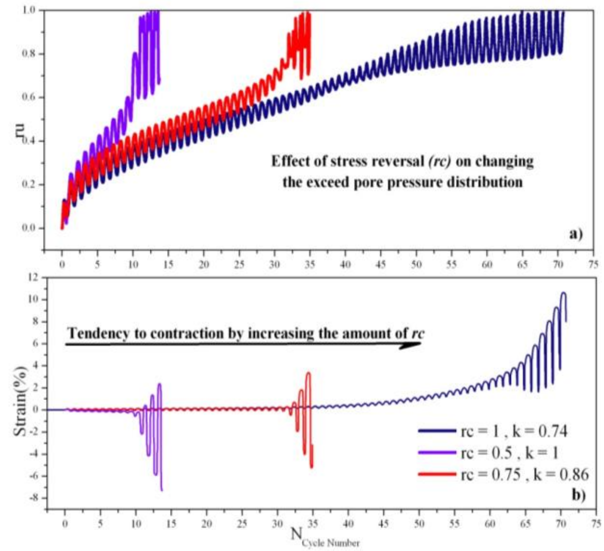



Figure 12 Effect of initial static shear stress (anisotropic consolidation) and stress reversal on the cyclic resistance of pure sand

### 6.3.2 Extensional consolidation or Negative initial static deviator stress

When the anisotropic consolidation is under *K* value larger than 1, the $\alpha$ will be negative and is called extensional consolidation here. Figure 13 shows the results of some tests with extensional consolidation and different stress reversal. As it can be seen in this figure, extensional consolidated pure sandy samples have more tendencies to have extensional residual strain with decreasing *rc*. In non-reversal conditions in fully extensional mode ($rc \le 0$), the residual strains are triggered from the first cycle. Also in this condition the generation of pore pressure is different from another extensional tests ($0< rc \le 0.5$). For non-reversal condition, in this case *(rc = 0, K =1.29)* the excess pore water pressure never reaches to the initial effective confining pressure and failure under large strain takes place instead of liquefaction. In fact the failure of the soil takes place in nonzero effective stress while the strain is very large and soil exhibited a very soft behavior. This means assuming the large strain as the criteria for liquefaction is more reasonable than the excess pore pressure criteria.

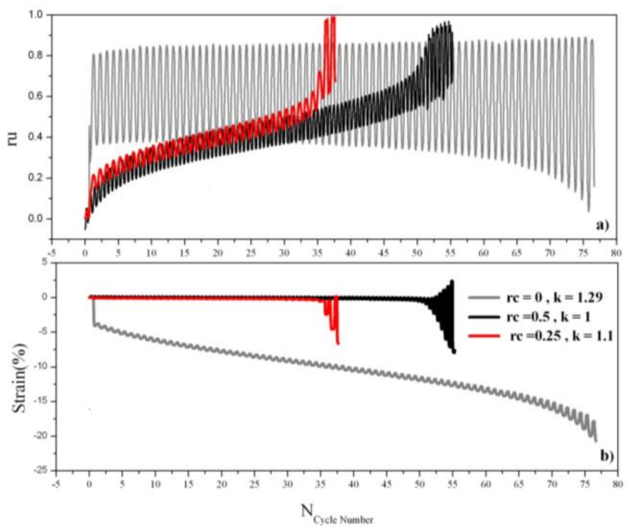



Figure 13. Effect of rc on a) distribution of excess pore water pressure and b) deformational behavior of extensional consolidated sandy specimens

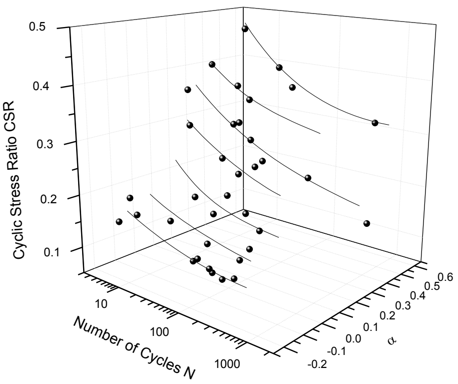



Figure 14 Effect of initial static shear stress ratio □ on the liquefaction resistance of saturated pure sand

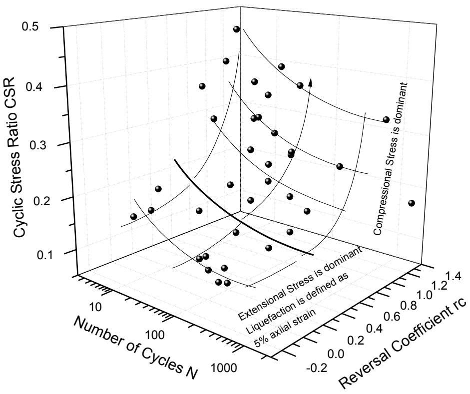



Figure 15 Effect of cyclic shear stress reversal coefficient rc on the liquefaction resistance of saturated pure sand

### 6.3.3 Discussion on the combined effect of rc and □

Figure 14 and 15 present all data with reference to the effect of a and rc. As it can be seen in Figure 14 variation of $\alpha$ from negative to positive values has caused increase of cyclic resistance with almost a constant rate. Change of cyclic stress reversal to compression drastically increased the cyclic resistant while in extension side the resistance is very low and almost has lees affected by rc. Since the data belong to all tests with different a and rc values, both factors have effect on the cyclic resistance. It is necessary to understand how both factors have combined effect.

Considering Eq 5, it is clear that the occurrence of stress reversal is dependent on the applied Cyclic Stress Ratio. The ratio of α/CSR can create different degrees of shear stress reversal. The resistance to liquefaction is therefore related to the amplitude of the applied cyclic stress. The followings are representing different situations that may happen in the case of different α and CSR values:

- If $\alpha/CSR<0$ then $rc<0.5$ then the extensional deviator stress will be dominant and smaller *rc* values will create weaker resistance to liquefaction (in terms of 5% double amplitude axial strain)

- If $\alpha/CSR=0$ then rc=0.5 and weakest resistance to liquefaction (in terms of 100% build up of excess pore water pressure) could happen

- If $0<\alpha/CSR<1$ then $0.5<rc<1$ and resistance to liquefaction (in terms of 100% build up of excess pore water pressure) will decrease

- If $\alpha/CSR>=1$ stress reversal will not happen and deviator stress will be in fully compression side and the highest resistance to liquefaction (in terms of 100% build up of excess pore water pressure) will happen

Considering the above information, one can conclude that the resistance to liquefaction in cases where there is an initial static shear stress is dependent on the amplitude of the applied Cyclic Stress Ratio too. CSR value can create either stress reversal or no stress reversal. Since shear stress reversal has effect on the resistance against liquefaction, therefore this factor should be taken into account together with initial static stress ratio α. Based on Eq.5 the ratio of α/CSR has a linear relation with *rc* and therefore is a suitable factor that can be correlated to a correction factor similar to $k_\alpha$.

The abovementioned discussion is based on the results obtained from cyclic triaxial tests. In real cases where the shear stress is more similar to the simple shear, the stress reversal and its occurrence and significance could be similar. However, careful study is necessary to prove the same observation about the simple shear case.

### 6.4 Effect of initial static stress and stress reversal on the liquefaction of silt mixed sand

Finding the effect of anisotropic consolidation on the behavior of sand-silt mixtures was the another scope of the current study. For this purpose another series of cyclic triaxial tests has been performed on different sand-silt mixtures. Anisotropic consolidation with different $K$ values and different reversal coefficients $rc$ were used in these tests.

Figure 16 shows the effect of stress reversal on the cyclic resistance of Firoozkuh sand mixed with 15% silt. $K$ factor was constant during the tests. As it can be seen in this figure when the $rc$=1 and the cyclic load was fully in compression side, the resistance was larger than those tests with smaller $rc$. This observation is very similar to the behavior of pure sand and deviator stress reversal has significant effect on the liquefaction potential of mixed sand-silt. Similar observations have been made for 30% silt mixed sand.

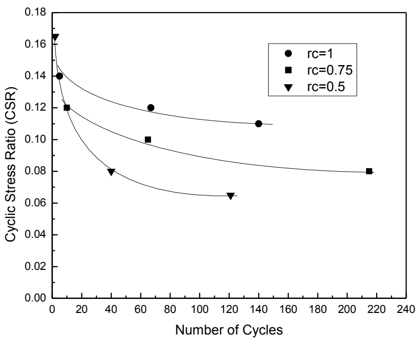



Figure 16 Effect of reversal coefficient on the cyclic resistance of Firoozkuh sand mixed with 15% silt

## 7. CONCLUSION

Results of 83 undrained cyclic triaxial tests on Firoozkuh sand and silt mixed sand were studied. In these tests specimens were tested under isotropic and anisotropic consolidation. To obtain the cyclic resistance of soil samples to liquefaction the cyclic deviator stress was applied with different amplitudes under undrained condition. The explained procedure created different initial static shear stress and also different reversal of cyclic deviator stress. Effect of different silt content is also investigated. The followings are the most important conclusions drawn from this study:

- Under isotropic consolidation, applying a symmetric cyclic stress history (equal compressional and extensional deviator stress) on sandy samples has caused an asymmetric strain history with larger strain in extension side. Anisotropy effect has caused a softer behavior in extensional loading mode ($q<0$). Adding 15 to70% non-plastic silt has caused a symmetric strain history. In other word, adding silt to the host sand has decreased or even eliminated the anisotropic behavior of pure sand.

- Adding 15% non plastic silt to the pure sand has caused a drastic drop in its cyclic resistance. Adding silt content more than 15% has gradually increased the cyclic resistance again.

- Anisotropic consolidation creates an initial static deviator stress. Moreover, the amplitude of cyclic deviator stress generates different amount of stress reversal. The stress reversal coefficient $rc$ is introduced and its relation with $\alpha$ (initial static shear stress ratio) and $CSR$ (Cyclic Stress Ratio) is derived.

- Results showed that the increase of $\alpha$ ($q_0>0$) caused increase in cyclic resistance. Negative $\alpha$ ($q_0<0$) made the cyclic resistance to decrease.

- Stress reversal was another factor affecting the cyclic resistance. When the cyclic stress had larger component in the compression side the cyclic resistance has increased.

- The ratio of $\alpha/CSR$ that is related to $rc$ can be considered to take the effect of $rc$ and $\alpha$ into account for correction of cyclic resistance ratio.

- Initial shear stress and stress reversal has the similar effect on the mixed sand and silt.

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