Effect of silt percents on liquefaction potential and anisotropic behavior of saturated sand-silt mixtures

L'effet de pour cent de limon sur le potentiel de liquéfaction et la conduite anisotropic de mixtures de limon de sable saturées

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ABSTRACT

The liquefaction potential of sand-silt mixtures is investigated in this study. There has been widespread debate over the effect of silt on the liquefaction resistance of saturated sand-silt mixtures. Some researchers have reported that by increasing the fine content the liquefaction resistance of the sand-silt mixtures increases. However, recent researches have shown that silty sands are more liquefiable than clean sands, which is in complete contradiction with the previous results. The first purpose of this study is to reveal the true effect of silt on resistance to liquefaction of sandy specimens by means of a series of load-control cyclic triaxial tests. These tests were conducted on sand-silt mixtures in various fine contents. In addition, the anisotropic behavior of the sand-silt mixtures was studied in this research by exploring the effect of the initial shear stress and stress reversal. The effect of stress reversal was studied by introducing a new parameter RC. The effect of this parameter was investigated in detail, and it was found that this parameter has a crucial role in the behavior of sand-silt mixtures.

RÉSUMÉ

Le potentiel de liquéfaction de mixtures de limon de sable est enquêté dans cette étude. Il y a eu la discussion étendue sur l'effet de limon sur la résistance de liquéfaction de mixtures de limon de sable saturées. Certains chercheurs ont dit qu'en augmentant le contenu parfait la résistance de liquéfaction des mixtures de limon de sable augmente. Pourtant, les recherches récentes ont montré que les sables limoneux sont plus liquéfiables que les sables propres, qui est en contradiction complète avec les résultats précédents. Le premier but de cette étude est de révéler le vrai effet de limon sur la résistance à la liquéfaction d'exemplaires sablonneux au moyen d'une série de contrôle de charge les épreuves de triaxial cycliques. Ces épreuves ont été accomplies sur les mixtures de limon de sable dans les contenus parfaits différents. En plus, la conduite anisotropic des mixtures de limon de sable a été étudiée dans cette recherche en explorant l'effet du renversement de tension et de tension de tondage initial. L'effet de renversement de tension n'a pas été considéré dans les recherches précédentes; pourtant, dans cette étude l'effet de ce paramètre est exploré en détail et il a été constaté que ce paramètre a un rôle crucial dans la conduite de mixtures de limon de sable.

Keywords: liquefaction, silt, anisotropy, triaxial

1 INTRODUCTION

There are many investigations about the effect of silt on the liquefaction resistance of sand-silt mixtures in the literature. These investigations are either based on in-situ or laboratory tests. Almost, all of the in-situ tests indicate the positive role of fines on reducing the liquefaction potential of sandy soils. This positive effect is also observed by some researchers in the laboratory tests(Yeh 1981, Kaufman & chang 1982, chang 1987, and Amini 2000). However, in recent years the majority of the researches have shown that by adding fines to sands the liquefaction resistance of these soils significantly decreases (Zlatovic & Ishihara 1995, Baziar & Dobry 1995, Lade & Yamamuro 1997, Thevanayagam et al 1998, Naeini & Baziar 2003). Due to these diverse observations, there are many controversies between different researchers about the effect of fines on the liquefaction potential of silty sands and the difference between the results of the in-situ and laboratory tests.

Pure sands show anisotropic behavior when they are anisotrpically consolidated. This kind of anisotropy is called induced anisotropy. Induced anisotropy reveals its effect in two ways: anisotropic resistance to liquefaction and anisotropic deformational characteristics. In this paper the anisotropic resistance to liquefaction of sand-silt mixtures is investigated.

In order to investigate the effect of silt content on the liquefaction potential and anisotropic behavior of sand-silt mixtures, 65 undrained cyclic triaxial tests were performed with various silt contents under isotropic and anisotropic consolidation. Furthermore, the reversal of the principal stresses was studied by defining a new parameter which is called Reversal Coefficient (RC).

2 MATERIAL PROPERTIES

FiruzKooh sand and silt were used in this study. The physical properties of the Firuzkooh sand are shown in table1. According to this table, Firuzkooh sand can be considered as fine sand. The plasticity index of Firuzkooh silt is less than 5 percent and it can be assumed as a Non-PI soil.

Table1. Physical properties of Firuzkooh sand

Sand	Gs	e_{max}	e_{min}	$D_{50\ (mm)}$	%FC	Cu	Cc
Firuzkooh	2.65	0.874	0.548	0.27	1	1.87	0.88

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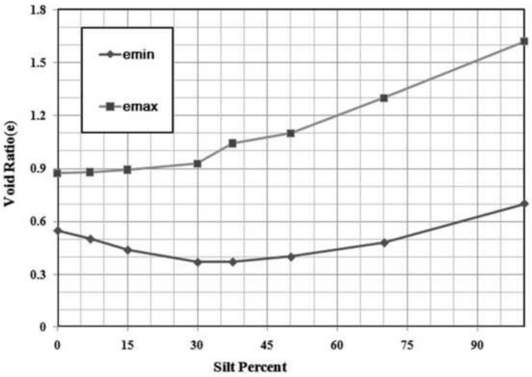


Figure 1. The minimum and maximum void ratio of sand-silt mixtures

Various amount of silt were added to pure sand. The amounts of silt in various specimens were 15, 30, and 70 percent. By adding silt to pure sand, the void ratio of the obtained sand-silt mixture decreases significantly. This trend was observed up to 25 percent of silt. However, in the specimens with silt contents greater than 25%, a reverse trend was observed, and the void ratio of the sand-silt mixtures increased by increasing the silt percent, which is due to the changing of the main skeleton from sand matrix to silt matrix. The minimum and maximum void ratios of sand-silt mixtures are depicted in Figure 1.

3 SAMPLE PREPARATION AND TEST PROCEDURE

In this study, a combination of the different types of the dry depositional method like DFD (Dry Funnel Deposition), TFD (Tapped Funnel Deposition), and FFD (Fast Funnel Deposition) was used for preparing the specimens. These methods of sample preparations are explained in detail by Yamamuro 2004.

After preparation of the specimens, the saturation stage was started. In order to saturate the specimens easily, according to ASTM D5311, Co2 gas was percolated through them for a specific amount of time. The minimum B-value of the 0.95 was obtained in all of the tests in order to substantiate the saturation of the specimens.

After saturation of the specimens, they were consolidated isotropically or anisotropically with different consolidation pressure ratio, K(=σ'c3/σ'c1). Subsequent to consolidation, a cyclic deviator stress (q = (σ'1 - σ'3)/2) was applied both in compression and extension modes. The applied frequency was about 0.05 Hz.

For considering the effect of stress reversal a new parameter was defined which is called RC (Reversal Coefficient). RC is the ratio of the compression domain of the deviatoric stress (the domain with q>0 or with σ'1 > σ'3) to double amplitude of the applied deviatoric stress (=2×q= (σ'1 - σ'3)). In isotropic condition (K=1), the amount of RC is equal to 0.5. The amount of RC in compression mode (K<1) is greater than 0.5, and, in extension mode (K>1), is less than 0.5.

4 APPARATUS

A cyclic triaxial device is used in this study. The apparatus is modified in such way that enables performing a fully computer controlled stress path. Cyclic tests are performed at Soil Dynamics Laboratory of University of Tehran.

5 RESULTS AND DISCUSSIONS

The results of the tests are presented in three sections; First: effect of fines on the liquefaction resistance of the isotropically consolidated pure sands, second: effect of anisotropic consolidation on the liquefaction resistance of pure sands, and third: the effect of fine content on the behavior of anisotropically consolidated samples.

5.1 *Effect of fines on the liquefaction resistance of the specimens under isotropic consolidation*

The Figure 2 and 3 show that increase of the silt to the specimens decrease the resistance to liquefaction of them and this decrease of resistance, in specimens with low silt percent is much more intense than specimens with high silt percent. The silt percent that the resistance to liquefaction has the lowest amount is about 25% and this amount of silt is called the critical silt percent.

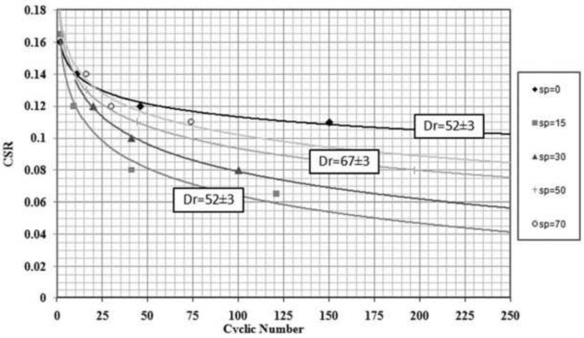


Figure 2. The minimum and maximum void ratio of sand-silt mixtures

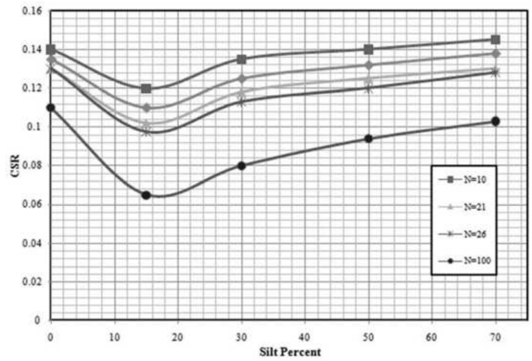


Figure 3. The minimum and maximum void ratio of sand-silt mixtures

Note:
According to Figures 2 and 3 the critical silt percent is 18%, while it must be about 25% according to the Figure 1 (The minimum emin is around 25%). This difference between the critical silt percent is due to the difference between the relative densities of sand-silt mixtures with different silt content. In the specimens with less than 25% of silt, the density ratio is about 52±3, and in specimens with more than 25% of silt this is about 67±3. The difference in the density ratios is due to the problems in preparing the samples with high silt percent. The minimum density ratio of the specimens with high silt content is 65%.

The main cause of decrease of resistance to liquefaction in silty specimens is the more tendency and capability to volumetric compressibility of them than pure sandy specimens. The emin graph shows the volumetric compressibility tendency of specimens and sand-silt mixtures approximately have less emin than sandy specimens then they have more tendencies to volumetric compressibility. On the other hand, the capability to volumetric compressibility of silty specimens is much more than sandy one, it must be considered that the capability to volumetric compressibility of specimens is different from their tendency to volumetric compressibility and it is related to both their mechanical characteristics (c and φ) and size of their main skeleton. The silty specimens have low mechanical characteristics and as a result, they have much more capability to volumetric compressibility than sandy one. Therefore, the more tendency and capability to volumetric compressibility make silty specimens more liquefiable.

But, why the resistance to liquefaction of sand-silt mixtures with silt content less than 25% is lower than sand-silt mixtures with higher silt percent. This trend is due to the less tendency and capability to volumetric compressibility of high silt percent specimens than low silt percent specimens. The lower tendency to volumetric compressibility is as a result of higher emin of high silt percent specimens and the lower capability to volumetric compressibility is due to the change of the main skeleton of the specimens from sand to silt. When the silt percent is less than 25%, the sand matrix dominates the behavior of the sand-silt mixtures, and the silt particles are completely surrounded by sand particles. In this case, the silt particles make the surface of the sand particles smoother and reduce its resistance and increase the volumetric compressibility of the mixture.

When the amount of the silt is greater than 25%, the silt skeleton is dominating, and the movement of the soil particles is limited, and the volumetric compressibility of the soil particles decreases significantly. This reduction in the movement of the soil particles is due to the different kind of the intergranular forces caused by very small dimension of the silt particles. The mean dimension of the silt particles is about 0.01 millimeter, which is about 1/20 of the dimension of the sand particles. Hence, the inter-particle contact forces of the silt particles are completely different from that of sands. As a result, the lower tendency and capability to volumetric compressibility of high silt percent specimens makes them less liquefiable than low silt percent specimens (silt percent lower than 25%).

5.2 *Effect of induced anisotropy on the behavior of sandy specimens*

The induced anisotropy is a kind of anisotropy obtained by anisotropic consolidation. The main parameter for introducing this kind of anisotropy is consolidation pressure ratio ($K=\sigma'3/\sigma'1$). The K parameter is an old and fundamental parameter for introducing induced anisotropy. Although this parameter is an effective parameter in this regard, it is not a comprehensive one because it does not consider the effect of the stress reversal and loading stage. In order to consider the loading stage, a new parameter (Reversal Coefficient (RC)) is introduced in this study. We can study the effect of anisotropy more accurately by investigating the effect of RC along with the effect of (K) on the behavior of the specimens.

5.2.1 *Specimens which were consolidated in compression mode*

Figure 4 shows the CSR-N diagrams of the specimens which are consolidated isotropically and anisotrpically. According to these graphs in the specimens which are consolidated in compression mode, the liquefaction resistance increases by increasing the in situ (primary) shear stress caused by decreasing the amount of the K parameter ($=\sigma'3/\sigma'1$). This is due to the reduction of the volumetric compressibility tendency of the anisotropically consolidated specimens.

In order to investigate the effect of the stress reversal on the liquefaction resistance of the specimens with constant amount of (K), we can observe the behavior of these specimens in various amounts of RC. According to Figure 4, when the amount of (K) is constant, the resistance to liquefaction of the specimens increase by increasing the amount of RC. The main reason of this trend is the increase of the volumetric compressibility tendency due to the increasing of the reversal of the shear stresses. To sum up, it was observed that by decreasing the amount of K or increasing the amount of RC, the resistance to liquefaction of the specimens will increase.

5.2.2 *Specimens which were consolidated in extension mode*

The specimens which were consolidated in extension mode collapse instead of liquefy. This phenomenon occurs since the induced cyclic stress increase the pore pressure in the specimens, which results in the reduction of the strength parameters. An important point which was observed in these tests was that even a small percent of stress reversal intensely diminishes the resistance of the specimens. In Figure 5, the diagram which relates to RC=0.25 indicates the detrimental effect of the stress reversal on the resistance parameters of this anisotropically consolidated specimens. On the other hand, in extensionally consolidated specimens which do not experience stress reversal, contrary to compressionally consolidated specimens, liquefaction resistance is lower than that of isotropically consolidated specimens. For example, in the specimens with K<1.28 the liquefaction resistance is lower than that of in isotropic condition. compressive consolidated specimens, resistance to liquefaction can be lower than isotropically consolidated specimens for example for K smaller than 1.28 the reverse condition occurs and resistance to liquefaction is lower than isotropic condition.

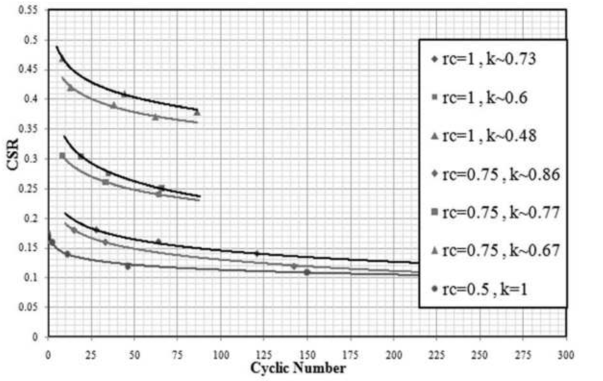


Figure 4. The CSR-N graphs of sandy specimens under compressive consolidation

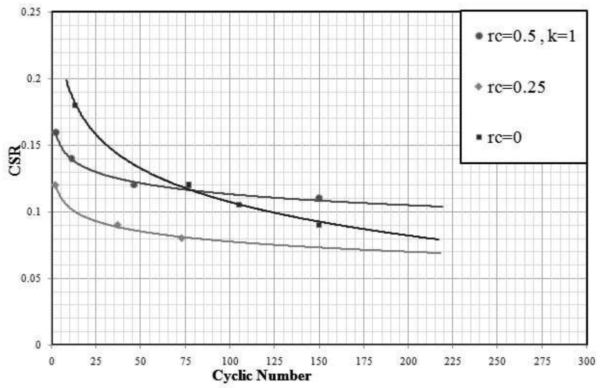


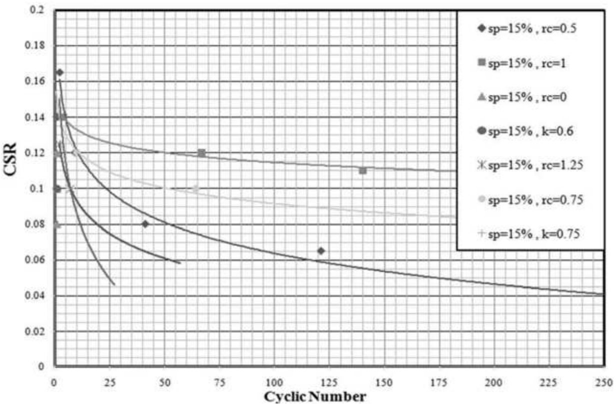
Figure 5. The CSR-N graphs of sandy specimens under extensive consolidation

5.3 *Effect of fine on anisotropically consolidated samples*

All of the above discussions were about the effect of anisotropy on the liquefaction resistance of pure sands. In this section, we want to explore this phenomenon when different amount of silt are added to pure sand. The results of the tests showed that by adding silt particles to pure sand, the effect of anisotropy on the behavior of the specimens is not the same as that effect in pure sands. For example, in the sand-silt mixtures which were anisotropically consolidated in compression mode, by decreasing the amount of (K) or by increasing the amount of RC, the liquefaction resistance of the specimens decreases, while the contrary behavior was observed in pure sands. The reason of this contrast is due to the convergence of the peak of the induced shear force and the peak of the shear strength. For example, in sand-silt mixtures with 15% of silt, the specimens with RC=1.25 are more liquefiable than the specimens with

RC=1, and the CSR-N line of these tests is located under that of specimens with RC=1. This trend was also seen in specimens with SP=30%; however, in this case, the CSR-N diagram of the specimens with RC=1 is beneath the diagram of the specimens with RC=0.75.

Besides, in the specimens which were consolidated anisotropically in the extension mode, there is no resistance to liquefaction and all of the specimens were liquefied just after one cycle, and their resistance was much less than pure sands. This elimination of the liquefaction resistance of the extensionally consolidated specimens in sand-silt mixtures is not approved by some researchers. In other words, some researchers believe that the liquefaction resistance of sand-silt mixtures is more than that of pure sands when they are consolidated in extension mode since these types of soils have cohesion (C) among their particles and the internal friction angle (φ) has less importance in their resistance. To justify this contradiction, we believe that other authors have thought that, in extension tests, the specimens were actually extended. However, in this study, "extension" means the reduction of the vertical stress, and the specimens were never extended in these tests.



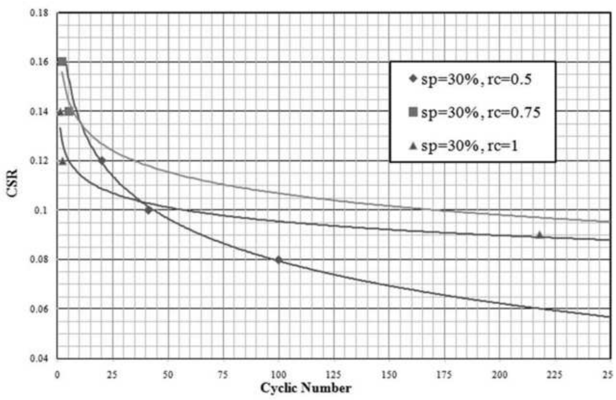


Figure 6. The CSR-N graphs of sand-silt mixture with 15% silt under isotropic and anisotropic consolidation

Figure 7. The CSR-N graphs of sand-silt mixture with 30% silt under isotropic and anisotropic consolidation

6 CONCLUSIONS

By increasing the fine content, the liquefaction resistance of the sand-silt mixtures decreases. The critical silt percent in which the liquefaction resistance has the least amount is 25%, and in this amount of silt, also emin has the minimum amount. By further increasing of the silt content, the liquefaction resistance increases; however, it is always less than the liquefaction resistance of the pure sand. This observation is in accordance with the findings of other researchers (Zlatovic & Ishihara 1995, Baziar & Dobry 1995, Lade & Yamamuro 1997, Thevanayagam et al 1998, Naeini & baziar 2003).

The liquefaction resistance of the anisotropically consolidated sands in compression mode increases by decreasing the amount of (K) and increasing the amount of RC.

The anisotropically consolidated sands in extension mode were not liquefied, and they were collapsed due to the tension fracture. These tests were very sensitive to stress reversal, and their resistance completely diminished when the stress reversal occurred.

In the sand-silt mixtures which were consolidated anisotropically in compression mode, by decreasing the amount of (K) or increasing the amount of RC, the liquefaction resistance increase but unlike the pure sand this trend can reverse in low K or high RC contents.

The sand-silt mixtures which were consolidated anisotropically in extension mode showed no resistance to liquefaction, and, nearly, all of the specimens were liquefied after one cycle and their resistance was significantly less than that of pure sands.

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