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Assessment of liquefaction behavior of Izmir sand reinforced with randomly distributed fibers

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ABSTRACT

This study focuses on the performance of randomly distributed fibers enhancing the liquefaction resistance of loose and medium dense sand deposits in Izmir, Turkey. A systematic testing program of stress-controlled cyclic triaxial tests was performed on saturated sand samples with and without fiber reinforcements under undrained conditions. The confining pressure for all test cases were 100kPa reflecting the actual overburden pressure in field conditions. The effect of parameters such as fiber content (0.25%, 0.50%, and 1%), fiber length (6 mm and 12 mm), and relative density (30% and 50%) on the liquefaction behavior of unreinforced and reinforced specimens was studied. Upon increasing the fiber content and fiber length, the number of loading cycles leading to liquefaction increased. The reinforcement effect in medium dense specimens was found to be more significant than that of looser specimens.

Introduction

The phenomenon of liquefaction in a deposit of loose sand under dynamic conditions is the development of excess pore water pressure and reduction of mean effective stress which corresponds to a complete loss of shear strength. Liquefaction can result in damages due to loss of bearing capacity, settlements of embankments, and lateral displacement of slopes. Condition of soil could be improved by reinforcement to reduce the risk of liquefaction. Soil reinforcement with randomly distributed fibers can be an alternative to decrease the liquefaction potential of soil structures. Compared to traditional soil reinforcing techniques, randomly distributed fibers have some advantages like prevention of potential weak planes which commonly develop parallel to oriented (planar) reinforcement; and maintenance of isotropic strength characteristics (Maher and Gray, 1990). The behavior of soil reinforced with randomly distributed fibers under static conditions was studied by researchers in the last decades (Krishnaswamy and Isaac, 1994; Vercueil et al., 1997; Consoli et al., 2009; Sadek et al., 2010). It was revealed that using fiber reinforcement in soil increased shear strength and ductility, and reduced post-peak strength loss. Recently, static liquefaction studies explored the possibility of fiber reinforcement to improve the liquefaction resistance of sand. These studies stated that the occurrence of lateral spreading could be prevented by using fiber reinforcement (Ibraim et al., 2010 and Liu et al., 2011).

The objective of this study is to characterize the liquefaction resistance of fiber reinforced sand specimens using cyclic triaxial tests. While most previous investigations have focused on the strength and deformation characteristics of fiber reinforced soil under static loads, this study

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explores through a series of laboratory experiments the effectiveness of randomly distributed fibers in improving liquefaction resistance of Izmir sand.

Materials and Methods

Test Materials

Clean sand is obtained from an excavation site from the city center of Izmir in Turkey. The sand is classified as poorly graded sand (SP) according to the Unified Soil Classification System. The effective size (D_{10}), the diameter corresponding to 30% finer (D_{30}), mean grain size (D_{50}), and the diameter corresponding to 60% finer (D_{60}) of the sand gradation are 0.15 mm, 0.28 mm, 0.53 mm, and 0.70 mm, respectively. The coefficient of uniformity is 4.67 and the coefficient of curvature is 0.75. The maximum and minimum void ratios are 0.84 and 0.56, respectively. The specific gravity of the sand is 2.67.

The monofilament polypropylene fiber materials used in this study were also produced in Turkey by a local company. The fibers were rectangular in cross section with a specific density of 0.91, tensile strength of 400 MPa, and elastic modulus of 1000-2500 MPa. Fiber lengths were 6 and 12 mm (Figure 1). Fiber ratios of 0.25%, 0.5%, and 1% were added to the specimens by dry weight of sand. Fiber-reinforced sand samples were prepared at the same dry density as that of unreinforced sand. The fibers to be added to the sand were considered as a part of the solids fraction in the void–solid matrix of the soil. The amounts of fibers added as a percentage of the dry mass of sand.

(a) (b)

Figure 1. Materials used in this study (a) 6 mm PP fibers, and (b) 12 mm PP fibers

Test Cases

An experimental program was prepared to investigate the influence of fiber reinforced sand specimens. The test cases are combinations of relative density of the sand, fiber length and fiber ratio (Table 1). In addition to the routine experimental program, certain randomly selected test cases are rerun to check the validation of sample preparations of similar density and loading conditions to verify the repeatability and the accuracy of the results.

Table 1. Test cases conducted in this study.

Relative density (D_r) (%)	Fiber length (FL) (mm)	Fiber ratio (FR) (%)
30	6	0
		0.25
		0.50
		1.00
	12	0
		0.25
		0.50
		1.00
50	6	0
		0.25
		0.50
		1.00
	12	0
		0.25
		0.50
		1.00

Test Equipment

The stress-controlled cyclic triaxial tests were performed using a DTC-S367 cyclic triaxial system by Seiken Inc. The main components of this system consist of vertical pressure loading unit with air and water panel, triaxial cell, pneumatic sine loader, an electric measurement unit including, pressure and displacement transducers and volume change transducer, strain amplifiers, and dynamic data acquisition system. The servo reservoir assembly includes a regulator for setting the required pressure, a reservoir to smooth out any changes in the air supply pressure, two water traps and two pneumatic servo valves for controlling confining and back pressures. Distribution panel controls all water flow, automatic volume change apparatus and the triaxial cell. The cyclic triaxial apparatus is equipped with a single column load frame, with a servo-pneumatic actuator with external displacement transducer. The high performance servo valve provides a sinusoidal vibration frequency between 0.001 to 10 Hz. Axial displacement was measured by means of a displacement transducer with a travel distance of 50 mm. Axial load was monitored using a bellofram cylinder type of load cell with a capacity of 2 kN, which is mounted inside the triaxial cell. Thus, it only measures the vertical loads applied to the specimen and a possible falsification of the measured values of vertical load because of piston friction is avoided. The clear acrylic cylinder of the triaxial cell has a working pressure of 1MPa. A double burette type volume change apparatus was located in the system that contains a transducer with a stroke of 25 ml to measure the volume changes of saturated specimens.

Specimen Preparation

The experiments are conducted on specimens with a diameter of 50 mm and a height of 100 mm. The specimen preparation technique similar to the undercompaction technique of Ladd (1978) was adopted. A porous stone and a single filter paper were placed on the pedestal. A cylindrical rubber membrane was attached to the pedestal and secured with O-rings. A split mold was placed on the lower plate of the triaxial cell, vacuum was supplied to the mold and upper part of the membrane was secured. The required amount of oven- dried sand was mixed with a calculated amount of fibers was divided into ten equal parts, and each part was carefully transferred into the mold and compacted using a wooden rod until the desired height was achieved. Top of each compacted layer was cleared off slightly before placing the next layer to promote proper bonding. A single filter paper and a porous stone were placed above the specimen. The ends of the rubber membrane were slipped to the specimen cap. The specimens are prepared according to JGS 0520-2000 and are subsequently tested according to JGS 0541-2000.

Test Procedure

The specimens are flooded with carbon dioxide followed by de-aired water, and back pressure is applied to saturate the specimens. Skempton's pore water pressure value (B) is verified to vary between 0.96 and 1.00. The specimens are isotropically consolidated to the desired effective stress, and stress-controlled undrained cyclic loading is subsequently applied. In the liquefaction tests, the loading sequence applies a certain number of cycles necessary to reach a specified level of cyclic stress under a frequency of 0.1 Hz until the specimen develops a double-amplitude axial strain (DA) of 5%. During cyclic loading, continuous records are obtained for the excess pore water pressure (u), cyclic axial strain (ε_c), and the cyclic deviator stress ratio applied to the specimen. Following the recommendations of JGS 0541-2000, two criteria are considered to define liquefaction. If the amplitude of cyclic axial load is relatively large, the number of cycles needed to cause liquefaction is accepted as the number of cycles needed to reach a maximum value of excess pore water pressure equal to 95% of the effective confining stress; otherwise, it is recognized as the number of cycles needed to reach a double amplitude of 5% of the axial displacement of the specimen. The experiments progress until all specimens reach 10% of the axial displacement.

Typical test results obtained from a cyclic triaxial test conducted on Izmir sand with a relative density of 30% and subjected to an effective confining pressure of 100 kPa are illustrated in Fig. 2. Stress path of the specimen is given in Figure 2a. Two-way cyclic loading, which involves a continuous sequence of compression and extension, was regularly applied to simulate dynamic conditions, which could be detected from the regular change of q/σ'_0 between +0.20 and -0.20. Figure 2b shows the variation of the stress path with the cyclic axial strain. At the beginning of the test, small cyclic axial strain was observed, but as the number of cycles increases, the strains became more dominant on the compression side reaching to an approximate value of 8%. The variation of pore water pressure with the number of loading cycles is shown in Figure 2c. The progress of the pore water pressure ratio with the number of cycles follows a steady trend. After 3 cycles, the pore water pressure ratio exceeds 95%, and this condition stimulates the cyclic axial strains to vary considerably over a wider range. In Figure 2d, when the pore water pressure ratio reaches 100%, it results in +8 and −5% strain levels for a total strain of 13%. The triaxial testing system used in this study is a stress controlled device and the compression and extension loads are applied equally as seen in Figures 2a and 2b. However, the relationship of number of cycles corresponding to the loads applied and the cyclic axial strain shifts to the compression side. The main reason is due to the system of the cyclic triaxial system.

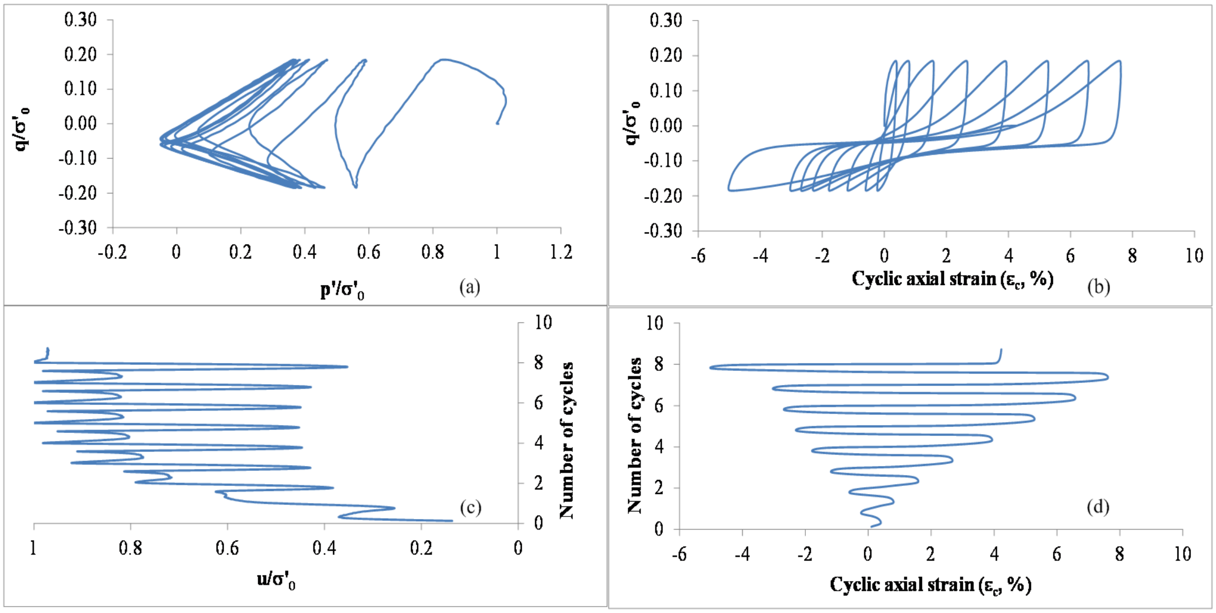

Figure 2. (a) Variation of stress path, (b) stress path with cyclic axial strain (c) pore water pressure ratio with the number of cycles, (d) cyclic axial strain with the number of cycles for a specimen of fiber reinforced Izmir sand (D_r = 30%, fiber length = 12 mm, fiber ratio = 0.25%, and σ_0' = 100 kPa.)

Results and Discussion

In this section, the main parameters of this study, namely as relative density, fiber length, and fiber ratio on the liquefaction resistance are presented and discussed. It should be noted that all the outcomes of this study belongs to the experiments which were performed under 100 kPa effective confining pressure. The liquefaction criterion of the tests was to achieve the number of cycles when the specimen developed a double-amplitude axial strain (DA) of 5%.

Effect of Relative Density

In Figures 3 and 4, variations of the cyclic stress ratio (CSR) with the number of cycles of fiber reinforced soils with relative densities of 30% and 50% percent are shown respectively. An increase in fiber length increases the number of cycles needed to cause liquefaction for the specimens having a relative density of 30%. For specimens having a relative density of 50% and fiber length of 6 mm, lowest liquefaction resistance was obtained from specimens having a fiber ratio of 0.25%.

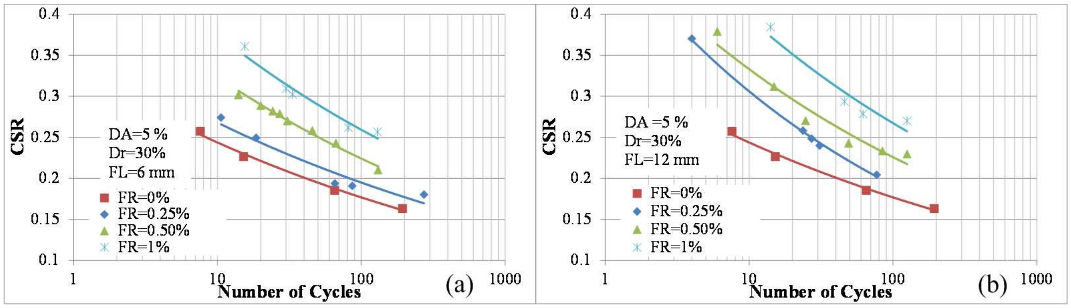

Figure 3. Variation of CSR with the number of cycles considering the effect of fiber length (a) FL= 6 mm (b) FL= 12 mm (FR: fiber ratio, D_r = 30% and σ_0' = 100 kPa.)

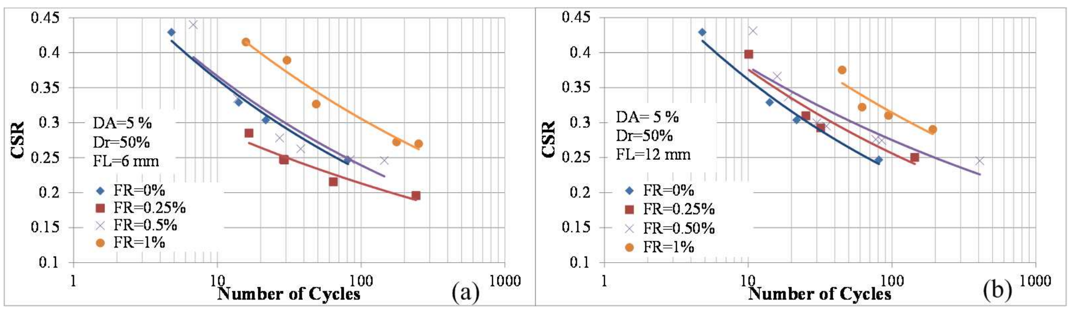

Figure 4. Variation of CSR with the number of cycles considering the effect of fiber length (a) FL= 6 mm (b) FL= 12 mm (FR: fiber ratio, D_r = 50% and σ_0' = 100 kPa.)

The specimens with a fiber ratio of 0.5% and the ones without fibers showed a similar liquefaction resistance. The highest resistance was achieved in specimens that contain 1% of fibers. For specimens having a relative density of 50% and fiber length of 12 mm, liquefaction resistance of specimens that contain no fiber, 0.25%, and 0.5% showed a liquefaction resistance varying in a narrow band. The most remarkable improvement against liquefaction was obtained in specimens with 1% fiber content. For medium dense specimens, at a constant fiber ratio the effective length of fiber available to mobilize shear strength increased with the increase in fiber length. In this condition, the probability of slippage occurring in fibers was reduced with an increase in fiber length, leading to better performance of fibers in soil.

Effect of Fiber Ratio

The fiber ratios of specimens were chosen as 0.25%, 0.5% and 1.0%. For all test cases, the liquefaction resistance was highest for specimens with D_r =50% and FL= 12 mm and it was lowest for specimens with D_r = 30% and FL = 6 mm (Figure 5). This finding is valid for all fiber ratios used in this study. Besides, medium dense specimens (D_r = 50%) with a fiber length (FL) of 6 mm showed the second best performance against liquefaction. This trend is followed in the same manner by loose specimens. This may be attributed to the fact that the voids from the matrix are fulfilled by the addition of fibers, leading to the additional matrix densification. This finding is in congruence with the results of Ibraim et al. (2010).

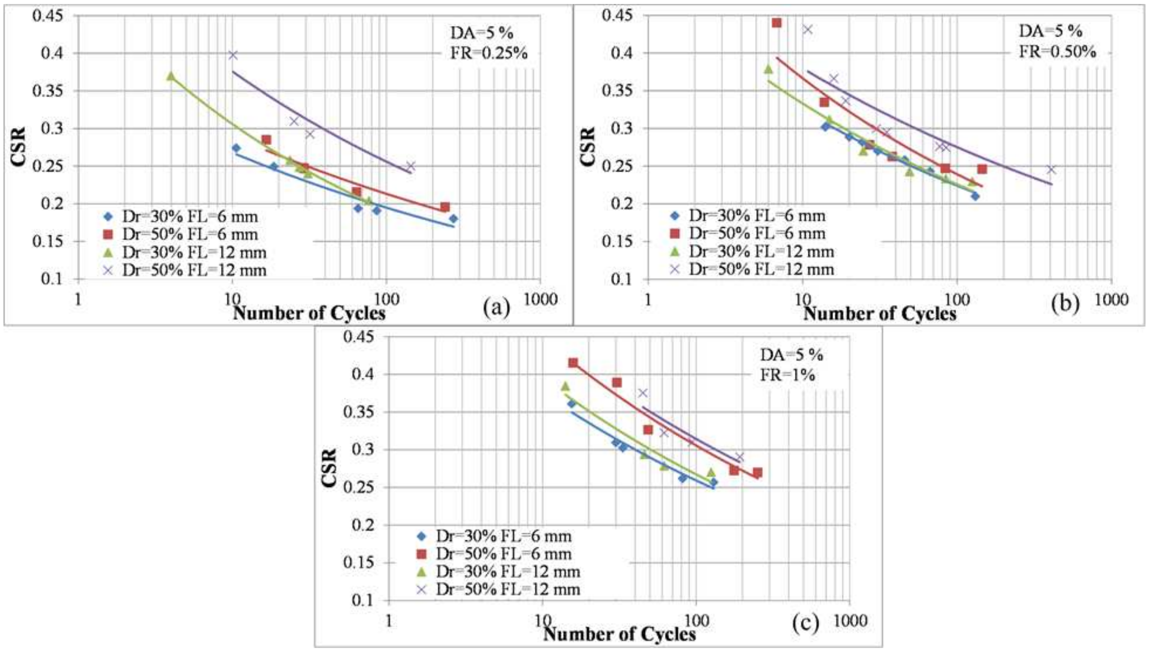

Figure 5. Variation of CSR with the number of cycles considering the effect of fiber ratio (a) FR= 0.25%, (b) FR= 0.50%, and (c) FR= 1% (σ_0' = 100 kPa.)

Effect of Fiber Length

The cyclic stress ratios corresponding to 20 loading cycles at a double-amplitude axial strain (DA) of 5% are given in Table 2. When the effect of fiber length is observed for fiber reinforced specimens, CSR values are greater for longer fibers (FL = 12 mm). As an example, CSR is 0.335 for medium dense specimens having a fiber ratio of 0.25 and fiber length of 12 mm, and CSR is 0.264 for medium dense specimens having a fiber ratio of 0.25 and fiber length of 6 mm. The increase in CSR is 27%. Therefore, it can be said that the increase in fiber length also improves the liquefaction resistance of Izmir sand. If a comparison is made between loose specimens with fiber ratios of 0 and 1%, improvement in liquefaction resistance is 52% for loose specimens that contain 6mm long fibers and improvement in liquefaction resistance is 59% for loose specimens that contain 12mm long fibers. There is a remarkable improvement in liquefaction resistance when Izmir sand is reinforced with randomly distributed fibers.

Table 2. Cyclic stress ratio (CSR) values corresponding to N_{cyc} = 20 loading cycles.

Fiber length (FL) (mm)	6		12	
Relative density (D_r) (%)	30	50	30	50
CSR_{20} (Fiber ratio (FR) = 1%)	0.336	0.399	0.351	0.409
CSR_{20} (Fiber ratio (FR) = 0.50%)	0.288	0.323	0.296	0.344
CSR_{20} (Fiber ratio (FR) = 0.25%)	0.244	0.264	0.266	0.335
CSR_{20} (Fiber ratio (FR) = 0%)	0.221	0.316	0.221	0.316

Conclusions

The following conclusions could be summarized in this study:

- The presence of fibers has a significant effect in reducing the liquefaction susceptibility. It was found that the number of cycles causing liquefaction increased with an increase in fiber ratio. Maximum improvement in liquefaction resistance was for sand specimens reinforced with 1% fiber at D_r =50%, and FL = 12 mm. The results clearly showed that fiber reinforcement is an effective technique in increasing the liquefaction resistance of Izmir sand.
- CSR values increased with the increase of fiber length. This is attributed to the development of a better mesh structure in the soil matrix as more grains can interrelate with a longer fiber.
- The liquefaction resistance of Izmir sand increases with an increase in relative density. The effect of reinforcement in medium dense specimens (D_r =50%) was found to be more significant than that of looser specimens (D_r = 30%).
- When the fiber reinforced specimens are compared with unreinforced specimens, the cyclic stress ratios corresponding to 20 loading cycles (CSR_{20}) increased 1.26 and 1.29 times for medium dense specimens having fiber lengths of 6 mm and 12 mm, respectively. However, CSR_{20} increased 1.52 and 1.59 times for loose specimens having fiber lengths of 6 mm and 12 mm, respectively. Therefore, it is seen that the fiber reinforcement is more effective for loose specimens.

Fiber reinforcement would be an efficient method in limiting or even preventing the occurrence of the lateral movement of the sandy soils due to liquefaction as normally observed for unreinforced sands. Further research is planned to focus on lateral spreading of fiber reinforced Izmir sand.

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