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Effect of fiber content on the liquefaction potential of improved soils

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Abstract

The use of randomly distributed fibers as soil reinforcement has recently become popular as a result of more satisfactory performance compared with those of the conventional reinforcements. Most previous investigations have focused on the strength and deformation characteristics of fiber-reinforced soil. The liquefaction behavior of fiber reinforced soils has recently received interest since fiber addition is currently considered as a new way of soil improvement to prevent soil liquefaction. Studies indicate that when soils are reinforced with synthetic or natural fibers, a reduction is observed in the number of cycles required to initiate liquefaction under undrained loading conditions. In this study, a regression analysis was performed by using the results of the previous studies. The obtained formula is able to capture the effect of fiber percentage and relative density of the cohesionless soil on the cyclic stress ratio values with a good agreement.

1. Introduction

Soil liquefaction can cause landslides, collapse of foundations, damage to soil structures, and lateral movement of structures standing on the ground. Therefore, it is important to consider the liquefaction potential of dams, embankments, slopes, foundation structures.

The liquefaction of saturated loose sands is defined as the loss of soil strength due to excessive pore pressures under seismic waves. During earthquakes, liquefaction causes reductions in the bearing capacity of soils and causes excessive settlements [1]. Basic liquefaction scheme is shown in Figure 1.

The occurrence of liquefaction has encouraged the interest of many investigators and remarkable work has been carried out to evaluate liquefaction susceptibility. Properties of soil could be improved by using reinforcement materials to eliminate the liquefaction hazard [2].

It has been revealed that the use of fiber in soils increases the shear strength of the soil, improves the flexible behavior and reduces the strength loss observed after the highest strength is reached. Recently, static liquefaction studies have investigated the possibility of fiber reinforcement to improve the liquefaction resistance of sand, these studies indicated that lateral spreading can be prevented by using fiber reinforcement.

Soil reinforcement with randomly distributed fibers was investigated by researchers in last few years and results showed that mixing fibers with granular soils improved liquefaction resistance and shear modulus of the soils.

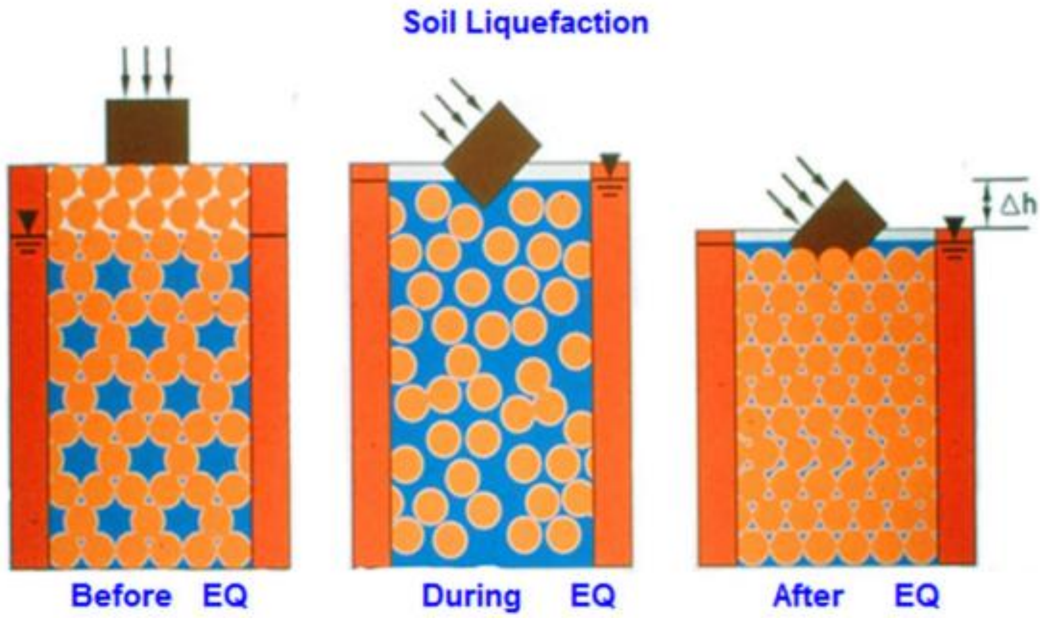

Figure 1. Liquefaction scheme [3]

2. Material and Method

It has been frequently used in recent years to obtain a homogeneous and clean soil with improved engineering properties, by randomly mixing the fibers produced from natural sources or artificially, which is a soil improvement method first researched in the laboratory and then used in practical engineering applications.

Soil reinforcement with fibers has some advantages compared to traditional soil reinforcement techniques. For example; mixing fibers with the soils is relatively easy with current soil mixing techniques and if homogeneous mixing is achieved, the fibers provide isotropic strength gain in the soil [4].

Basically, in this technique, which is developed by considering the contribution of plant fibers or roots to the stability of the soil, the fiber-soil mixture can reach very high shear strength values compared to the nonreinforced soil. Because, the fibers have higher tensile strength compared to the soil. For this reason, it is thought that the fibers will be efficient especially in soils near to the surface where the effective stresses and accordingly the shear strength are low.

Additionally, fibers mechanically change the failure mechanisms of cracks that may occur due to tensile stresses in the soil and prevent serious strength loss in the soil [5].

Although there are various investigations about strength and deformation characteristics of fiber-reinforcement soils under static loads, the studies on under cyclic loading are very limited in the literature.

In order to understand the liquefaction behavior of fiber reinforced soil, a series of ring-shear tests and a series of cyclic triaxial tests have been carried out on soil samples with different fiber content and sand density.

3. Literature Review

Jin Liu et al. [6], carried a series of undrained ring shear tests on saturated samples with different fiber content and sand density percentages to understand the effect of fiber content and sand density on the liquefaction behavior of fiber-reinforced sand. Fiber-free and fiber-reinforced samples were prepared using a moist compression technique. This technique is widely used in laboratory studies of fiber-reinforced sand and allows control of sample density while preventing fiber separation.

To analyze the results of shear tests on fiber-reinforced saturated sand, the samples were separated three groups as loose, medium dense and dense samples.

In loose samples, fiber addition did not significantly affect the undrained shear behavior, but samples without fiber added after shear showed a completely collapsed structure, while reinforced samples retained structural stability even after removal of the top ring. This situation is shown in Figure 2.

Figure 2. Liquefied loose specimens after shearing: (a) Sand; (b) fiber 0.4% [6].

As seen in Figure 3 and Figure 4, the presence of fibers obviously affected the undrained behavior of medium density and dense samples.

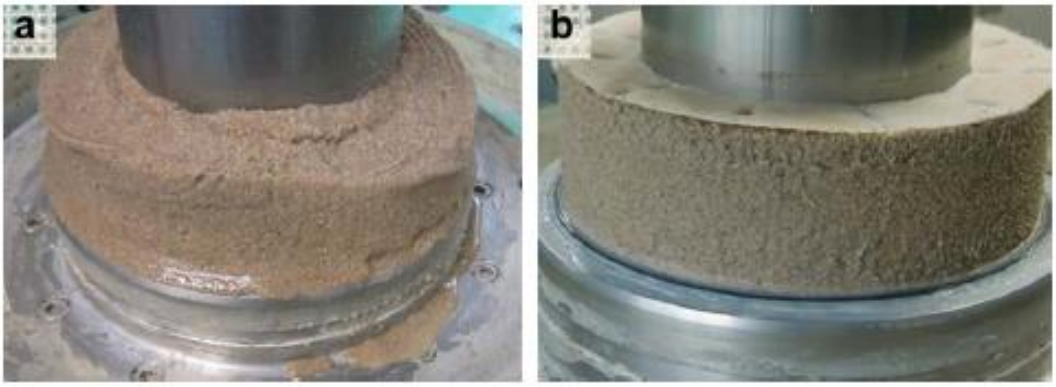

Figure 3. Liquefied medium dense samples after shearing: (a) Sand; (b) fiber 0.4% [6].

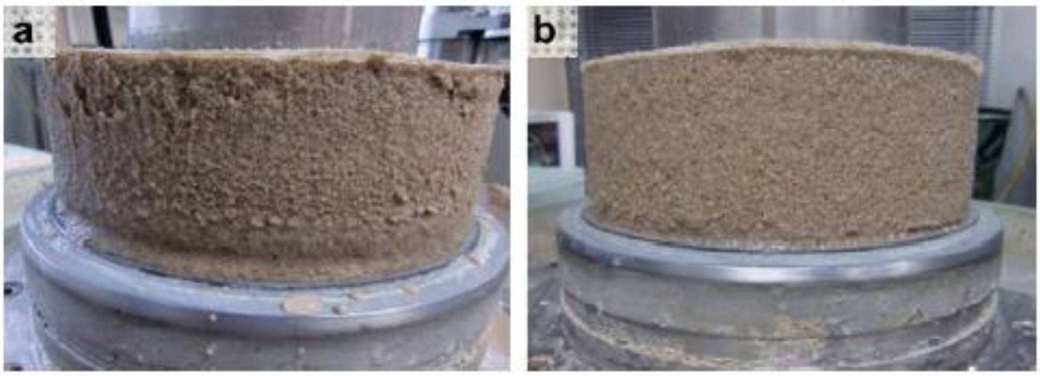

Figure 4. Liquefied dense samples after shearing: (a) Sand; (b) fiber 0.4% [6].

The results indicated that tests on sand samples showed a continuous decrease in shear strength after the sand was sheared, while samples with added fiber showed fluctuations even after shearing. This fluctuation is further strengthened by increasing fiber content. All reinforced medium density and dense samples retained structural stability, while the medium density sample without added fiber showed a partially collapsed structure and the dense sample showed little structural stability.

Noorzad et al. [7], aimed to characterize the liquefaction resistance and shear modulus of the sand-fiber mixture using cyclic triaxial experiments. The effects of test parameters and fiber properties on the liquefaction resistance and shear modulus of non-fiber and fiber-added samples were investigated.

As a result of the experiments, it is seen that the number of cycles required for liquefaction to occur increases with the increase in fiber content. By adding the fibers to the sand soil, the soil grains are better interlocked and at the same time, an easy homogeneous distribution is achieved.

An increase in fiber length has been found to increase the number of cycles required for liquefaction to occur, although the fibers are less effective during the initial cycles. In this case, the probability of slippage in the fibers decreased with increasing fiber length, resulting in better performance of the fibers in the ground.

Sonmezer [8] investigated the liquefaction potential of sandy soil reinforced with 0.25-1.00% polypropylene fiber using a stress-controlled cyclic shear test and an energy-based approach.

6, 12 and 19 mm long polypropylene fibers were used to reinforce the soil. The fibers used have a diameter of 0.031 mm, a specific density of 0.9, a tensile strength of 400 MPa and a modulus of elasticity of around 1000-2500 MPa.

The aim of the study was observing the effect of fiber reinforcement in loose sand layers saturated with water and with high liquefaction potential during an earthquake, mostly samples with 30% relative density were tested. However, to investigate the effect of relative density, tests were also conducted on a few samples with 50% relative density.

In the tests, the cumulative energy values of the fiber reinforced sand samples were obtained until the beginning of the liquefaction occurrence.

As a result of the tests, the area under the curve decreased as the number of cycles increased. The reason for this decrease was explained as the increase in excessive pore water pressure, and at the time of liquefaction, the area under the loop was greatly reduced and the hysteresis loop took an almost flat shape.

When the results of the study are examined, the cumulative energy, depending on the increase in fiber length as well as fiber content; increased with increasing number of cycles until liquefaction occurred.

It was observed that the liquefaction resistance of fiber-reinforced samples increased significantly with the increase in fiber content and length, especially when compared to non-fiber-reinforced samples. This increase is thought to be due to the increase in the shear strength of the soil sample due to the presence of fibers. This showed that fibers mixed with sand clearly had a significant effect on the liquefaction susceptibility of sandy soil.

In addition, the presence of fibers strongly influenced the evolution of pore water pressure. In other words, the increase in excess pore pressure in the presence of fibers is very slow. The same result is valid for both the increase in fiber content and the increase in fiber length. This is thought to be due to the fact that the fiber is an extensible material, increasing the energy absorption capacity of the sand.

Karakan et al. [9], aimed to determine the liquefaction resistance of fiber reinforced sand samples and the development of pore water pressure by applying cyclic triaxial tests. The effect of fibers in improving the liquefaction resistance of poor grade sand was investigated with a series of dynamic tests. The test sets contain samples with 0%, 0.25%, 0.5% and 1% polypropylene fiber content and two different fibers (6 mm and 12 mm) lengths. The relative density of the samples was 30%, 50% and 70%, representing different hardness states of the soil, and the samples were consolidated under a confined pressure of 100 kPa. In addition, a cyclic loading frequency of 0.1 Hz was applied to the samples.

When the experimental results were examined, an increase in fiber length increased the number of cycles that would trigger liquefaction for samples with a relative density of 30%. Additionally, the lowest liquefaction resistance for samples with 50% relative density and 6 mm fiber length was obtained from samples with 0.25% fiber ratio.

Moreover, the highest liquefaction resistance was obtained in samples containing 1% fiber. For samples with a relative density of 50% and a fiber length of 12 mm, the liquefaction resistance of the fiber-free samples showed a liquefaction resistance varying in a narrow band of 0.25% and 0.5%. The most remarkable improvement against liquefaction was obtained in samples with 1% fiber content.

Muley et al. [10], in their work; the effect of natural fiber, namely coconut fiber, on the liquefaction susceptibility of Solani River fine sand was investigated using tension-controlled undrained cyclic triaxial tests performed in accordance with ASTM D3999. The tests were carried out with samples prepared at 35% relative density and different fiber contents (0%, 0.25%, 0.50% and 0.75%). The inclusion of fibers significantly affected the results, and the specific gravity values of the mixed soil decreased continuously due to the increase in fiber content, while the maximum and minimum void ratio increased.

Chegenizadeh et al. [11], investigated the effect of fibers on the liquefaction resistance of low plasticity silt by performing a series of dynamic triaxial tests on fiber-reinforced and non-fiber-reinforced samples. The results showed that increasing the fiber content and length increased the liquefaction resistance of the samples, whereas with an increase in the relative density (Dr), the liquefaction resistance of the fiber-reinforced sample became more marked than that of the unreinforced sample.

Vercueil et al. [12], performed an experimental study (cyclic triaxial tests) of the liquefaction resistance of Hostun sand reinforced with geosynthetics. The results showed that the liquefaction resistance considerably decreases with fiber addition.

Bhandari and Han [13], carried out studies on the behavior of the geotextile and the soil under a cyclic wheel load using discrete element method. They reported that the geotextile has a major effect on the degree of interaction between the geotextile and the soil.

Altun et al. [14], conducted several stress-controlled cyclic torsional shear tests to investigate the effect of geosynthetics in increasing the resistance to liquefaction of Toyoura sand. The results showed that the liquefaction resistance of sand deposits can be remarkably improved by geosynthetic reinforcement.

Maher and Woods [15], studied the dynamic response (i.e.,shear modulus and damping) of sand reinforced with randomly distributed fibers using resonant-column and torsional shear tests. They reported that the addition of fibers enhances the dynamic modulus of cohesionless soils.

Ibraim et al. [16], investigated the static liquefaction behavior of fine sand reinforced with discrete crimped polypropylene fibers in both triaxial compression and triaxial extension tests. They found that the presence of fibers diminishes the potential of liquefaction.

Chen and Loehr [17], studied the behavior of fiber reinforced soil in the triaxial experimental setup under with and without drainage. They found that the soil strengths of the fiber-reinforced specimens under drained conditions exceeds the respective values of the same specimens under undrained conditions at low deformation levels.

Makiuchi et al. [18], reported that the strength and ductility of fiber-reinforced soils are properties that help build earthquake-resistant structures. They also proposed a method using synthetic fiber in their study.

Ashmawy and Bourdeau [19] explored the effect of geotextile reinforcement on the stress–strain and volumetric behavior of sand subjected to monotonic and cyclic loading. They conducted a series of drained triaxial tests on saturated sand samples reinforced with woven and nonwoven geotextiles. The results showed that the presence of reinforcement resulted in a significant increase in monotonic shear strength and ductility of sand and a reduction in cyclic deformability. Furthermore, under both monotonic and cyclic loading, a reduction in volume change potential was observed by the geotextile reinforcement.

Krishnaswamy and Isaac [20], observed that the inclusion of fiber significantly increased liquefaction resistance of sands. Authors used polypropylene, needle-punched and natural fiber as reinforcing material. It was observed that the reinforcement effect was more pronounced at lower densities.

Sharma and Kumar [21], reported that the strength and bearing capacity of the fiber-reinforced soil increased considerably with an increase in the relative density. Moreover, the previous researchers reported that the fibers can increase the ductility and liquefaction resistance of the soil.

The tests carried by Sadek et al. showed that a 0.5 to 1.5 % fiber content in the soil increases the shear strength values of the specimens [22].

Erken et al. [23] carried that the dynamic strength values of sand specimens saturated to water increase with increasing fiber ratio.

Shuai-dong and Xiang-juan [24] studied the cyclic behavior of reinforced silty sand by performing consolidated undrained cyclic triaxial tests. The dynamic elastic modulus of reinforced soil was reported to increase due to reinforcement, confining pressure, and consolidation stress ratio, as to the unreinforced soil.

4. Results and Discussion

The studies on the behavior of soils reinforced with randomly distributed elements under cyclic loading is very limited in the literature since the studies are about the strength properties of fiber reinforced soils. Investigators noted that that the number of cycles causing liquefaction increased with an increase in fiber ratio and CSR values increased with the increase of fiber length. Since, application of dynamic triaxial and torsional shear tests are significantly difficult, a regression analysis were performed in the current study by using the results of the previous studies. A sample of the used data is depicted in Table 1.

Table 1. A summary of the results derived from previous studies

Fiber Percent (%)	Dr (%)	Fiber Length (mm)	CSR
1	30	6	0.336
0.5	30	6	0.288
0.25	30	6	0.244
0	30	6	0.221
1	30	12	0.351
0.5	30	12	0.296
0.25	30	12	0.266
0	30	12	0.221
1	50	6	0.399
0.5	50	6	0.323
0.25	50	6	0.264
0	50	6	0.316
1	50	12	0.409
0.5	50	12	0.344
0.25	50	12	0.335
0	50	12	0.316

Based on the multiple variate regression analyses, the following equation was obtained.

$$CSR = a + bF_p + cD_r + d\left({}^{F_p}/_{D_r}\right) + e(exp\left({F_p}^3{D_r}^3\right) \quad (1)$$

In this equation, CSR represents the Cyclic Stress Ratio whereas F_p, and D_r denotes fiber percent and soil relative density, respectively. The constant parameters of *a, b, c, d* and *e* will be taken as: 0.5481, 0.2832, 0.2328, -0.04756, -0.4001, respectively. The graphical representation of the multivariate regression analysis was shown in Figure 5. The coefficient of determination is found as 0.90 for the suggested formula.

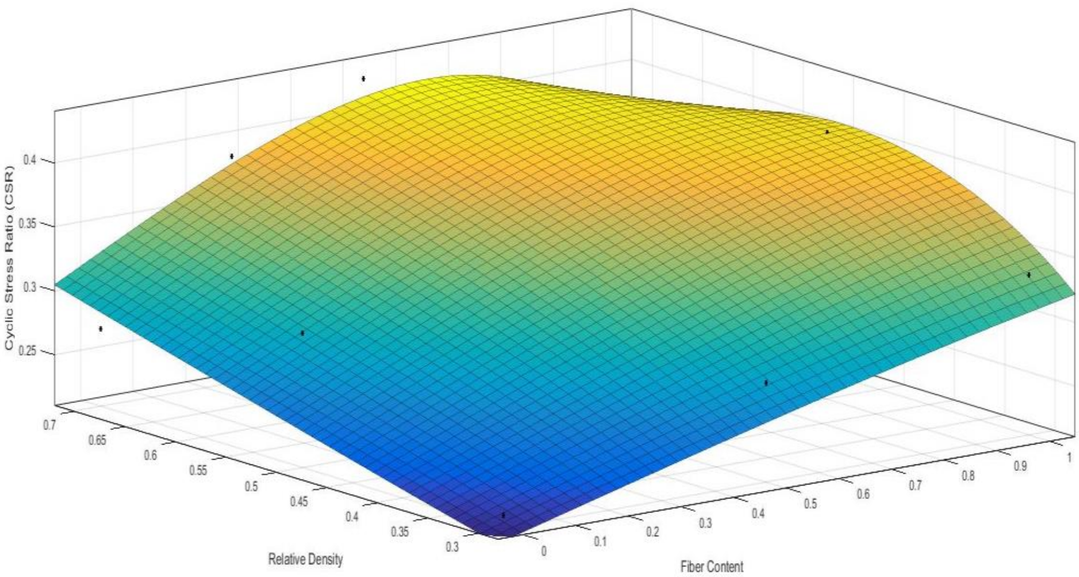

Figure 5. Graphical depiction of the multivariate nonlinear regression modeling results

5. Conclusion

Fiber reinforcement is an efficient method in limiting or even preventing the occurrence of the lateral movement of the sandy soils due to liquefaction. The presence of fibers affects the behavior of sand in cyclic compression by increasing the cyclic strength therefore liquefaction hazards or deformations appear to diminish. The cyclic test results showed that the addition of randomly distributed polypropylene fibers increases significantly the liquefaction resistance of sands at low relative densities. Since, application of dynamic triaxial and torsional shear tests are significantly difficult, a regression analysis were performed in the current study by using the results of the previous studies. The obtained formula is able to capture the effect of fiber percentage and relative density of the cohesionless soil on the cyclic stress ratio values with a good agreement (R^2=0,90).

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Author contributions

Özgür Lütfi Ertuğrul: Data curation, Validation, Writing-Reviewing and Editing. **Fatma Dülger Canoğullari:** Investigation, Writing- draft preparation.

Conflicts of interest

The authors declare no conflicts of interest.

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