Liquefaction potential of reinforced sand with plastic wastes

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Abstract: Granular soil liquefaction, due to developed pore water pressure during undrained cyclic shear of saturated soils, is regarded as a common phenomenon under earthquakes loading. This phenomenon results in the huge damage to infrastructures. Various reinforcement materials have been successfully implemented with particular attention to use waste materials to satisfy design specifications and also reducing the adverse environmental effects. This paper investigates the possibility of using waste plastic fibers as a reinforcement material to mitigate liquefaction potential and pore pressure generation of reinforced sand under cyclic loading. For this purpose, 42 stress-controlled cyclic triaxial tests were conducted on Babolsar sand, reinforced by polyethylene terephthalate (PET) and polypropylene (PP) fibers with fiber contents of 0.25%, 0.5% and 1%, under confining pressures of 50, 100 and 200 kPa, and with cyclic stress ratios (CSR) of 0.2 and 0.35. Results revealed that the addition of these waste plastic fibers could significantly increase the liquefaction resistance of Babolsar sand, and also, with an increase in the waste content, the number of cycles leading to liquefaction increased. Adding wastes decreased the pore water pressure generation, and this effect was more pronounced with an increase in the waste content.

Keywords: Cyclic triaxial test; Liquefaction; Pore water pressure; Reinforced sand; Waste plastic fibers.

1. Introduction

Since the horrible damage caused by liquefaction during the 1964 Niigata earthquake, many researches have been performed on the different properties of liquefaction [1]. Liquefaction is the most catastrophic form of geotechnical failure, which triggers commonly due to rapid development of pore water pressure (PWP) and decrease in effective confining pressure [1-4]. The liquefaction process usually converts the state of a soil element from solid to liquid [5] and results in significant damage to structures supported on such soils [6], e.g., bearing capacity loss, floating of manhole, embedded structures, buried tanks and pipes, ground surface settlement and lateral spreading [2].
Improving soil characteristics to reduce the liquefaction potential of soil is one of the areas that has attracted the attention of many researchers [7]. Soil reinforcement is a reliable technique to increase the stability and strength of soil in different applications, including embankments, retaining structures, slopes, foundations and pavements [8, 9]. The use of randomly distributed fiber for soil reinforcement was presented in the early 1970s, and quickly it became the subject of many studies. Fibers are commonly available in vast amounts in waste and natural forms [3, 9]. Previous studies showed that using various types of fibers for soil reinforcement increases the strength and bearing capacity of soils [10-13].

Furthermore, Population growth and the widespread use of bottles and plastic materials have led to overproduction of these materials. Since the decomposition of these materials takes a long time, the accumulation of these materials in the environment causes environmental problems [14-16]. Therefore, recycling and reuse of these plastic wastes has become one of the major challenges throughout the world. As some of these wastes are not biodegradable, they cause many environmental pollution problems for the surrounding environment [17]. Plastic waste is one of the most important municipal solid wastes due to the increase in sales and use of plastic packaging [18]. Currently, there is a great need for determining a practical solution for the disposal of waste plastics or reuse them as an alternative material in civil and industrial applications [19]. In many regions, waste fibers such as old tire and plastic waste fibers have raised some concerns regarding their disposal and their impact on the environment [19]. Utilization of the fibers in construction projects can overcome the disposal concerns of these wastes in an environmentally friendly and cost-effective manner [19]. Despite the high resistance, durability, and simple mixing of these plastics, the reuse of these materials has received less attention in geotechnical projects [16]. Recently, some researches have been
conducted on the possible applications of fibers in the soils and other materials, such as mine tailings and coal ashes [9].

Saturated and near saturated soils, under excitation of severe dynamic loads, such as earthquake loading, are prone to liquefaction. Soil liquefaction is defined as the state of suspension of the soil particles, as a result of release of contact between soil particles [20]. With regard to different soil conditions, the term liquefaction can be described.

Initial liquefaction defined as the state in which the pore pressure was close to initial confining pressure. In other words, this state occurs when the excess pore water pressure ratio reaches 1.0. In this case, the increase in axial strain became substantial. This phenomenon was primarily seen in loose sands. The second type of liquefaction, known as limited liquefaction, or cyclic mobility, happens in medium-dense to dense sand. In these soils, because the achievement of zero effective stress was impermanent, the following softening was temporary and did not lead to collapse. Instead, as loading progressed, the specimen recovered its stiffness and strength because of dilation. This state largely defined by occurrence of about 5% double amplitude axial strain (DAAS) or development of 100% excess PWP ratio. Once developed 100% excess PWP ratio, large (NOT drastic) strain accumulation (not strain softening) occurs in every loading cycle. However, deformation thereafter does not increase indefinitely, and complete loss of strength does not take place in the sample even after the onset of initial liquefaction [20-24]. In contrast ishihara (1993) has defined cyclic instability as follows: "None the less, some degree of softening takes place in the sample accompanied by a sizeable amount of cyclic strain, and it has therefore been customary to consider the state of 100% pore water pressure build-up or the development of 5% DAAS as a criterion by which to recognize a state of cyclic instability covering a wide range of density of sand" [20]. In this case the excess PWP undergo a drastic

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and sudden increase in the process of loading, attached with abrupt and rapid straining. Cyclic instability (flow liquefaction) can be triggered before reaching excess PWP ratio of 100%. Once triggered, strain accumulation is drastic (or even continue without impose of any additional loading—that’s why also referred as flow liquefaction), and sample fully liquefied (like liquid) within few loading cycles. This phenomenon commonly observed for loose saturated granular soils [21-24]. The main difference between the initial liquefaction and the limited liquefaction is that in limited liquefaction, the complete loss of strength did not taken place. In silty sands or sandy silts containing some amount of fines, the pore water pressure is observed not to develop fully, but to stop building up when it has reached a value equal to about 90%-95% of the initial confining stress. However, a sizeable amount of cyclic strain is observed to develop, indicating considerable softening taking place in these soils [21-24]. Thus, the occurrence of 5% DA axial strain in the cyclic triaxial test is used below as a criterion to define coherently the state of cyclic softening or liquefaction of soils, from clean sands to sands containing fines. Clayey cohesive soils, subjected to cyclic loading usually not lose complete strength, even in saturated condition. The behavior of clayey material is characterized by strength degradation with the number of cycles and the accumulated strain [25].

2. Background

The use of tensile elements to improve the soil strength has begun 3000 years ago, when Iranians and also Babylonians had used a combination of straw and soil as a building material [26]. Over the past decades, the field and laboratory studies have revealed that the utilization of waste, synthetic, and natural fibers as a tensile component leads to significant improvement and adjustment in the mechanical properties such as compressibility, stiffness, strength and permeability of soils [9, 10]. Different mitigation methods have been successfully executed to
decrease the liquefaction potential and its subsequent effects [27]. Vercueil et al. [28] and Altun et al. [6] studied the liquefaction of reinforced sand with geosynthetics. Their results showed that resistance of sand deposits liquefaction could be considerably increased with geosynthetic reinforcement [28]. Besides conventional reinforcing techniques such as geogrid and geotextile reinforced earth, using randomly distributed fibers as reinforcement material has gained more popularity because of more acceptable performance [2, 29].

Many studies have been performed to evaluate the effects of fiber inclusion on liquefaction potential of reinforced soil. Noorzad and Amini [2] studied the liquefaction and shear modulus of reinforced Babolsar sand with polypropylene (PP) fibers under cyclic triaxial loading with different confining pressures. It was concluded that the confining stress has a significant effect in decreasing the liquefaction potential, and adding fibers appreciably increases shear modulus and liquefaction resistance of sand [2]. Other researchers also reported similar observations, indicating that fibers improve the shear modulus and liquefaction resistance of soil [30-33]. Dahal [27] conducted a laboratory research on shear parameters and liquefaction potential of reinforced sand by PP fibers. Results indicated that reinforced samples did not exhibit initial liquefaction as compared to unreinforced samples, although resistance against liquefaction increased with the inclusion of fibers [27]. Eskisar et al. [29] found that there is a direct relationship between the loading cycles number and the generation of excess PWP in reinforced sand. Krishnaswamy and Thomas Isaac [5] performed triaxial tests to assess the liquefaction potential of reinforced sand by geotextile, including coir fibers and woven and nonwoven types. The results showed that reinforcing significantly increase the liquefaction resistance of sand [5]. Furthermore, they studied the size effect of samples by considering different sample sizes. It was shown that larger specimens demonstrate a greater resistance
against liquefaction [5]. Hence, it is rational to lean on the smaller samples results to evaluate the reinforced sand liquefaction potential.

Benson and Khire [34] studied behavior of reinforced soil with strips of reclaimed high-density polyethylene (HDPE). Results indicated enhanced strength and resistance against deformation, which depended on the aspect proportion (or length) of strips [34]. Babu and Chouksey [35] showed that plastic waste fibers inclusion improves the resistance of the soil and reduces its compressibility. This can be beneficially used in settlement reduction and improvement of bearing capacity in shallow foundations design [35]. Meddah and Merzoug [36] evaluated the shear strength properties of sand reinforced with rubber fibers in the dense and loose state with fiber percentages of 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75 and 2% of the sand dry weight. Their results revealed that the rubber fibers use in the dune sand is not only the environmentally friendly method but also it improves the peak strength, residual strengths, and characteristics of shear strength, and makes the mechanical behavior of sand more ductile [36]. Banerjee et.al. [37] studied the liquefaction potential of cohesionless soils under near saturated condition through a series of cyclic triaxial tests on consolidated undrained specimen. Several tests carried out with different CSR (the ratio of the cyclic deviator stress to the initial confining stress), range from 0.15 to 0.35. Results indicated that the failure mechanism in all specimen, which were moderately dense cohesionless soils, were cyclic mobility. It was shown that the soil specimen in near saturated condition need higher CSR and/or higher number of load cycles to liquefy.

Keramikerman et. al.[38] performed a series of cyclic triaxial tests on fly ash stabilized sand to assess the liquefaction resistance of stabilized sand with fly ash under cyclic loading. They studied the effects of relative density (Dr of 20% to 80%), FA content (2% to 6%), different confining pressure (50 kPa to 90 kPa), as well as curing time liquefaction resistance (0 to 28
days). Results revealed that at a constant relative density, with different confining pressure, specimens with higher FA content shows a greater liquefaction resistance. In addition, they showed that the specimen curing can decrease the liquefaction potential.

Liu [39] performed a large number of cyclic triaxial tests to evaluate the influence of fine contents on soil liquefaction resistance. A total of 96 cyclic triaxial tests on the uniform medium Monterey sand with six different percentage of fine content, as well as 198 cyclic triaxial test on the uniform medium concrete sand with five different percentages of fine content. For the tests, the effects of different relative densities (Dr of 30% to 60%), different confining pressure (from 103 kPa to 207 kPa), and six different stress ratio (from 0.2 to 0.45) were studied. Results indicated that adding fine contents up to 12% in clean sand may cause an increase in the tendency to liquefaction, while after 20% of fine content, the liquefaction resistance increased.

Most of the previous studies on reinforced soils with plastic waste have focused on shear strength and deformation characteristics under static loading even though information on the impact of plastic waste on liquefaction potential of sand under dynamic loading is rather limited. Therefore, this study aims at providing technical data on the cyclic triaxial behavior of sand reinforced with waste PET and PP fibers with 0.25, 0.5, and 1% of weight of dry sand. In particular, the effect of waste fibers on liquefaction potential and PWP generation of samples was investigated by using stress-controlled cyclic triaxial tests.

3. Experimental program

3.1. Materials

3.1.1. Babolsar sand
The experiments were carried out on clean, uniform, quartz Babolsar sand with specific gravity of 2.74 (based on ASTM D854-14 [40]) and the maximum and minimum void ratios of 0.86 (corresponding to \( \gamma_{d,\min} = 1.48 \) g/cm\(^3\), based on ASTM D4254-16 [41]) and 0.58 (corresponding to \( \gamma_{d,\max} = 1.74 \) g/cm\(^3\), based on ASTM D4253-16 [42]) respectively. Based on the Unified Soil Classification System, ASTM D2487-17 [43], the soil was classified as poorly graded sand (SP). For the tested sand mean grain size \( (D_{50}) \) was 0.17 mm and the curvature and uniformity coefficients were 1.3 and 1.8, respectively. Figure 1 shows the grain size distribution curve of Babolsar sand, which was determined according to ASTM D422-63 [44].

3.1.2. Polyethylene Terephthalate (PET) fibers

PET is a light and crystal material; it is the most common polymer resin of the polyester family. Its density is 1.34 g/cm\(^3\) and in a temperature of more than 72 °C, it transforms to a plastic state [16]. To produce PET fibers, first, waste bottles are grinded into bottle chips and then heated by well-equipped machines in a controlled condition to produce PET fibers. In this study, the length of the fibers was selected equal to 15 mm and specimens were prepared with fiber content of 0.25%, 0.5%, and 1% by weight of dry sand. An overview of producing these fibers is shown in Figure 2.

3.1.3. Sack Polypropylene fibers

Sack polypropylene (PP) plastic is resistant against acidic and alkaline environment, also has an acceptable tensile strength. PP plastic used in this study was provided from waste materials of a gunny production plant. Its density and melting temperature were 0.9 g/cm\(^3\) and 170°C, respectively. In this research, discrete PP fibers were manufactured by cutting the plastic wastes to a length of 15 mm. As it is shown in Figure 3, single fiber's width is approximately 2–
2.5 mm. In this paper, the PP fibers content were selected in various contents including 0.25%, 0.5%, and 1% of the soil dry weight. An overview of these fibers is shown in Figure 3.

### 3.2. Test equipment

In this research, the stress-controlled cyclic triaxial tests were conducted using a MTM Global apparatus. The overall view of cyclic triaxial apparatus is presented in Figure 4.

The board was used to display and control the applied loads inside and outside the sample during saturation, consolidation, and loading phases. Two onboard gauges were also included to visually observe the pressure and suction values. In addition, three graduated burettes were included on the board in order to monitor the Top Back Pressure (TBP) and Bottom Back Pressure (BBP) to provide the required water. By using these burettes, the amount of input and output water of the sample were determined. Furthermore, to control the amount of input and output water, two valves were also installed on the board. Besides, electrical sensors for capturing the water pressure and controlling the valve to set the cell pressure were provided as well. The range over which the sensors can precisely work was from zero to 1000 kPa [16].

The loading frame applies the loading on a sample. This part of the apparatus includes a base, two columns, a beam, and a loading jack. To control and observe the data, three electrical parts including a server valve, a load cell, and a displacement sensor were installed on the loading frame. The capacity of the load cell used in this study, was up to 500 kg, and the displacement limit for the sensor was 50 mm. The sample was placed in a cell, which could bear the pressure up to 850 kPa. There were four valves below the cell, each of which had a specific function: one was for applying the cell pressure, one was for applying the top back pressure, and
the other two were for applying the bottom back pressure or drainage. In addition, the controlling system includes the sensors, operators, a data logger, and a processing software.

3.3. Sample preparation

Previous studies have shown that sample preparation method has a considerable effect on the reinforced soil behavior [45]. In this research, cylindrical samples were prepared with 50 mm diameter and 100 mm height using moist tamping method in 5 equal layers to achieve relative density of 40% for specimen before consolidation, which was equal to 1.57 g/cm³ of sand mixtures dry unit weight.

In order to evaluate the efficiency of sample preparation methods, different methods (wet/moist tamping, air pluviation, water sedimentation and undercompaction techniques) were examined in the laboratory and homogeneity of samples were evaluated. Eventually, a moist tamping method using undercompaction technique which has been proposed by Ladd [46], was chosen for the preparation of samples. This technique is usually used for preparing fiber reinforced sand in laboratory and allows to control the density of samples, as well preventing segregation [45, 47]. Moreover, this method simulates the in situ condition almost accurately [47]. It is suggested to add water to the sand to achieve a better mixture of sand and fiber to the amount that it does not cause them to float [2]. In this work, to determine the required amount of water for preparation of samples, different water contents including 5%, 10%, and 15% were considered and the homogeneity of samples was evaluated. Based on the results, 10% water content was determined as the optimum moisture content to prepare the sand-fiber mixtures.

To prepare the samples, the oven dried sand was blended with the required amount of water. Then, the fibers were added at different percentages and thoroughly mixed by a
mechanical mixer. Figure 5(a) and Figure 5(b) show sand mixtures with PET and PP fibers, respectively. Furthermore, due to the lack of cohesion in sand-fiber mixtures, it is necessary to directly prepare the samples in the split mold of the triaxial apparatus. For this purpose, the mixture was apportioned to five equal parts, then each portion was cautiously poured into a split mold with a special spoon. Afterwards, the layer was compacted with a tamper until the desired height. To minimize the effects of bedding error, under-compaction method was used. In this method, to achieve a uniform compacted sample, each layer is compacted to a lower density than the final desire value by a predetermined amount of undercompaction ratio. The method is described in details in [46]. For this purpose, the height of layers from bottom to top was considered to be 21.6 for first layer, 41.2 for the second layer, 60.8 for the third layer, 80.4 for the fourth layer and 100 mm for the last layer, respectively. To make sure that the layers’ height were correctly compacted, as shown in Figure 6(a), the height of each layer was controlled by a caliper. Moreover, before pouring the next layer, in order to create a proper interconnection between layers, it is recommended to slightly scratch the surface of each layer [16]. Figure 6 demonstrates a prepared specimen for reinforced sand with PET fibers at fiber content of 0.5%.

3.4. Test procedure

In this research, 42 cyclic triaxial tests were performed on Babolsar reinforced sand based on ASTM-D5311[48] provisions. The detailed experimental program is presented in Table 1. After preparing the specimen in the apparatus mold and before the mold disassembly, to stabilize the specimen, a 10 kPa vacuum was applied (Figure 6-b). Then, the triaxial device cell was prepared and filled with water. Afterwards, the cell pressure of 10-15 kPa was applied to the specimen to be able to remove the applied vacuum pressure without manipulating the relative density of specimen. This provide an isotropic confining pressure for the specimen. In the next
step, the sample was saturated to fill all the voids in the specimen using de-aired water without undesirable pre-stressing or swelling. For this purpose, first, carbon dioxide (CO$_2$) was percolated slowly (1-3 kPa) through the specimen for more than one hour to replace air bubbles with carbon dioxide in the specimen voids [16]. Since carbon dioxide is dissolved in water easier than air, the process of saturation becomes simpler. Next, distilled de-aired water was permeated from the base to the cap of the specimen with a low pressure, till the total amount of passed water from the sample became more than two times of the initial volume of the specimen. The use of de-aired water also decreased the time and back pressure required for saturation. Subsequently, cell pressure and back pressure were increased step by step with sufficient time between increments to enable equalization of water pore pressure throughout the sample. It should be noted that, to avoid consolidation of the specimen during saturating process, the difference between the back pressure and cell pressure was kept almost constant at 10 kPa.

The sample saturation was continued until the B value [16] reaches to 0.95 or higher. An overview of a sample after saturation process is shown in Figure 6-c. To consolidate the samples isotropically, the cell pressure was increased at a constant back pressure of 300 kPa, till the difference between cell pressure and back pressure became equal to a wanted effective confining pressure, which was selected as 50, 100 and 200 kPa in this study.

Two-way stress controlled cyclic loading tests were performed on the unreinforced and reinforced consolidated specimens under the undrained condition with a loading frequency of 1 HZ. A cyclic stress ratio (CSR=$\frac{q_{cy}}{2\sigma_{3}}$) of 0.2 and 0.35 were used to simulate medium and severe earthquakes that are relevant for the studied region. Axial loading, axial strain, and excess pore water pressure were measured within the intervals of 0.001 s and the test results analyzed/compared with these obtained values for different samples. Based on the relative
density of the samples, which were loose-medium sand, the expected liquefaction scenario for unreinforced samples were initial liquefaction, while for the reinforced samples, with both PP and PET fibers, the cyclic mobility was expected. In this research, the liquefaction is specified, where the double amplitude of axial strain (DAAS) over cyclic loading reaches 5% [48].

4. Results and discussion

The axial strain time history, the ratio of excess water pore pressure, and the applied deviator stress, for reinforced sand with PET fibers at CSR values of 0.2 and 0.35 are shown in Figure 7 and Figure 8, respectively. It is observed from the Figure 7(a) and Figure 8(a) that applying constant cyclic deviator stress increased the axial strain gradually, until the DAAS of 5% (liquefaction criterion) was reached. The ratio of excess water pore pressure that was specified as the ratio of developed excess water pore pressure to the effective confining stress ($r_u=\Delta U/\sigma'_3$) [48], increased gradually with time. Figure 7(b) and Figure 8(b) show the development of $r_u$ for these two samples. As it is observed, the generated $r_u$ within the specimen periodically changed during cyclic loading, while its value increased in each loading cycle in a cumulative manner. As can be seen, both specimens reached initial liquefaction ($r_u=1$) before failure, while for the unreinforced sand, the initial liquefaction and failure occurred at the same time. More details on this are provided below.

4.1. Effects of fiber content

The resistance of reinforced Babolsar sand against liquefaction according to the relation between the CSR and relating numbers of required cycles to lead liquefaction (DAAS of 5%) for both two types of used fibers and different contents of them is depicted in Figure 9. It is obvious
from the figure that for both two types of plastic wastes, the resistance of Babolsar sand against liquefaction is improved by increasing the fiber content.

Figure 10 and Figure 11, show the variation of required cycles number to reach the liquefaction against the waste fibers content for reinforced samples at different confining pressures. It can be concluded from these figures that soil reinforcement (with both two types of plastic wastes) had a considerable effect in decreasing the liquefaction potential. For example, the number of cycles leading to liquefaction is changed from 57 for the unreinforced sand to 115 for the 1% PET reinforced sample at 50 kPa confining pressure and CSR of 0.2. The corresponding values at CSR of 0.35 and for 1% PP reinforced sample are 7 and 13 respectively. Actually, the resistance of reinforced sand against liquefaction increased with increasing content of fiber, which was in consistent with the behavior observed by previous researchers [3, 6, 27, 30-33]. This effect may be ascribed to the fact that using plastic waste fibers as reinforcement improves interlocking of soil particles, and it also results in uniform distribution of PWP within the samples. Since the plastic waste reinforced sand was subjected to deformation, the friction appearing between soil and plastic wastes could develop the tensile stress in the plastic wastes, and this tensile stress leads to increase of sample confinement. Due to this confinement, the freedom of movement of sand grains decreases. As a result, less pore water pressure develops due to cyclic loading on the sample. Finally, this factor improves the liquefaction resistance of reinforced sample compared to the unreinforced one. Boominathan and Hari [30] and Noorany and Uzdavines [33] also reported improvements in liquefaction potential of fly ash and sand due to the use of mesh/fiber components.

Figure 12(a)-(d) shows the stress-strain curve (hysteresis loops) for PET reinforced sand with various contents of fiber at 100 kPa confining stress and CSR of 0.2. As it can be seen,
unreinforced sand exhibited a sudden growth in axial strain, and reached a DAAS of 5% (liquefaction criterion) in fewer cycles (36 cycles); however, for the reinforced sand, increase in axial strain against applied cyclic loading is occurred gradually, and also, the required cycles number to attain the liquefaction criterion has increased. This behavior was more noticeable with a growth in the fiber content (i.e., for 1% PET reinforced sample, 74 cycles are required to reach the liquefaction). Furthermore, reinforced samples demonstrated an inelastic behavior and the mean slope of the loops decreased from cycle to cycle, which is indicating stiffness degradation of these samples over cyclic loading.

The development of excess PWP ratio ($r_u$) for unreinforced and reinforced (with both two types of plastic wastes) sand at different confining pressure (CP) and CSR value of 0.2 are shown in Figure 13(a)-(c). As it can be observed from the figure, the rate of PWP development in the unreinforced sand is rapid and the initial liquefaction state ($r_u=1$) occurs in fewer cycles of applied cyclic loading, while in the reinforced sand (with both two types of plastic wastes), this rate is significantly reduced and the initial liquefaction state is reached in more cycles. Actually, it can be stated that the inclusion of fibers in the sand delays its initial liquefaction state due to the dilation of the sand, which cause to a decrement in PWP throughout the specimen. Noorzad and Fardad Amini [2] and Maheshwari at al. [7] reported same results for reinforced sand with other types of fibers. Another point that can be concluded from the figure is that in the initial cycles of loading, excess PWP increased rapidly and the effect of fiber inclusion was negligible. In fact, fiber presence was ineffective for values of $r_u$ lower than 0.2. This behavior could be due to the fact that during the first cycles, the strain level as well as the deformation was low and as a result, the required extension to engage fibers in tension was not met; therefore, adding fibers was less effective in the first cycles. Eskisar et al. [29] reported the same result and stated that
the rate of PWP generation for reinforced sand with PP fibers at confining pressure of 100 kPa in
specimens with \( r_u < 0.5 \) is greater than those with \( r_u > 0.5 \).

However, with a growth in confining stress and CSR value the effect of fiber inclusion on
the development of PWP in initial cycles was more apparent. As shown in Figure 14, for the
specimens tested at CSR value of 0.35, fiber inclusion in the sand led to a reduction in
development of PWP in initial cycles. In fact, in this case, because of the high degree of
confining stress and CSR value, the deformations are large enough to cause interaction between
fibers and sand particles.

4.2. Effects of fiber type

In this study, two types of monofilament plastic waste with the length of 15 mm have
been used: PET fibers, which are hairy with a negligible thickness and also PP fibers that are in a
form of 2-2.5 mm wide narrow strips (as shown in Figure 5). Results of the tests performed on
the PET reinforced sand are compared with PP reinforced sand in Figure 15 for different CSR
values. As it can be observed, at both CSR values, PET fibers were more effective in increasing
the resistance against liquefaction and also in less development of PWP of the reinforced sand as
compared to PP fibers.

As discussed previously, having a homogeneous mixture is one of the prerequisites to
obtain the reliable results. The use of both PET and PP fibers in the sand led to the homogeneous
mixtures. In comparison to PP fibers, PET possessed a greater surface area which reduced the
slippage potential of fibers and this factor led to more improvement of the liquefaction resistance
of PET reinforced sand than the PP reinforced one.
4.3. Effects of confining pressure

Another point that is clear from the Figure 10 and Figure 11 is that at a certain percentage of fiber, the number of cycles leading to liquefaction has decreased with increasing confining pressure. This conclusion is contrary to the previously reported results such as Noorzad and Fardad Amini [2]. The reason for this discrepancy can be attributed to the remaining constant of CSR in this research with increasing confining pressure. In fact, according to the definition of CSR, in order to keep its value constant, the amount of applied shear to the sample increased with increasing confining pressure, which reduced the number cycles causing liquefaction.

Moreover, to better understand of the impact of confining pressure, the relation between the CSR and the relating number of required cycles leading to liquefaction for varying confining pressure in unreinforced and PP reinforced sand with the fiber content of 0.5% is depicted in Figure 16. As it is observed, at moderate loading (CSR value of 0.2), the impact of confining stress is more considerable in liquefaction resistance of reinforced sand than the sever loading (CSR value of 0.35). Also, the variation of magnitude of deviatory stress (CSR value) has less effect on soil liquefaction resistance of deep soils (high confining pressures) than the surface soils (low confining pressures).

4.4. Cyclic mobility

Instability under cyclic loading is discovered to be created by cumulative development of axial strain (cyclic mobility) until liquefaction occurs, rather than the gradual development of excess PWP [49]. Time history of axial strain for unreinforced and PP reinforced sand for CSR values of 0.2 and 0.35 are depicted in Figure 17-18, respectively. As it is observed, the unreinforced specimens suddenly reached the DAAS of 5% as an indication of liquefaction. On
the other hand, the inclusion of plastic waste fibers caused cyclic mobility in the specimens, which resulted in gradual increase of strain until failure. For example, at the CSR of 0.2, the PP reinforced sample with the fiber content of 1% (Figure 17-d) reached to the failure criteria at 52 cycle numbers, while this value for the unreinforced one (Figure 17-a) was 23 cycle numbers. This outcome shows that fiber inclusion in the sand leads to a good improvement in cyclic behavior of it. In fact, reinforcing low density sand by plastic fibers changed its behavior and it became partly similar to the unreinforced dense sand (due to the occurrence of dilation) [15], which was more noticeable with increasing fiber content.

5. Summary and conclusions

This paper investigated the effect of adding waste PET fibers and PP fibers on liquefaction resistance and PWP development of Babolsar sand under cyclic triaxial loading. For this purpose, 42 cyclic triaxial tests were performed on randomly distributed fiber reinforced sand in undrained condition. According to the results of the experimental program, the important conclusions are as follows:

- Soil reinforcement with waste plastic had a significant effect on decreasing the potential of liquefaction. For example, the number of cycles causing liquefaction is changed from 57 for the unreinforced sand to 115 for the 1% PET reinforced sample at 50 kPa confining pressure and CSR of 0.2. This effect was due to the fact that using fibers as reinforcement improved the interlocking between soil particles.

- PET fibers were found to perform better than PP fibers as a reinforcement material. According to experimental observations, these fibers exhibited better interaction and greater
contact surface with sand particles, which escalated their performance and led to more desirable results.

- Adding fibers clearly decreased the PWP development because of occurrence the dilation in reinforced sand. Due to the presence of fibers, PWP easily developed along the specimen, which cause a conversion in the type of liquefaction from initial liquefaction (in unreinforced samples) to cyclic mobility (for reinforced samples).

- In the initial cycles of loading, because the required extension to engage fibers in tension was not met, excess PWP increased rapidly and the impact of fiber inclusion was insignificant. However, with a growth in confining stress and CSR value that led to create large enough deformations and in consequence cause interaction between fibers and sand particles, the impact of fiber inclusion on the progress of PWP in initial cycles was more apparent.

- The unreinforced specimens are prone to initial liquefaction, as the excess PWP ratio suddenly reached 1, while inclusion of plastic fibers resulted in cyclic mobility, which led to a gradual increase in strain before failure. Noteworthy to mention that the cyclic mobility was specified when reaching the 5% DAAS.

- Under high deviatory stress the impact of confining stress is more considerable in improving the liquefaction resistance of reinforced sand. The variation of the deviatory stress magnitude has less effect on liquefaction resistance of soils with high confining pressure (deep soil conditions), than the soils with low confining pressure (surface soil condition).

**Conflict of interest**

The authors confirm that there are no known conflicts of interest associated with this publication.
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**Table Captions:**

Table 1: Summary of the characteristics of the test

**Figure Captions:**

Figure 1: Grain size distribution of Babolsar sand

Figure 2: a) Waste bottle, b) Bottle chips, c) Showered down fibers, d) PET fibers in length of 15 mm

Figure 3: a) PP fibers, b) PP fibers in length of 15 mm

Figure 4: Cyclic triaxial apparatus

Figure 5: Reinforced sand with a) PET fibers, b) PP fibers

Figure 6: a) Control layers height by caliper, b) Specimen before triaxial cell assemblage, c) Specimen after saturation

Figure 7: a) Time history of axial strain, b) Time history of excess pore water pressure ratio, c) Time history of deviatory stress, for reinforced sand with PET fibers

Figure 8: a) Time history of axial strain, b) Time history of excess pore water pressure ratio, c) Time history of deviatory stress, for reinforced sand with PET fibers

Figure 9: Number of cycles leading to liquefaction versus cyclic stress ratio at a) CP = 50 kPa, b) CP = 100 kPa, c) CP = 200 kPa

Figure 10: Number of cycles causing liquefaction versus at various confining pressure for reinforced sand with a) PET fibers b) PP fibers for CSR = 0.20

Figure 11: Number of cycles causing liquefaction versus at various confining pressure for reinforced sand with a) PET fibers b) PP fibers for CSR = 0.35

Figure 12: Stress-Strain hysteresis for reinforced sand with different PET content at CP=100 kPa and CSR = 0.20
Figure 13: Pore water pressure generation at various fiber contents at CSR = 0.20 with a) CP = 50 kPa, b) CP = 100 kPa, c) CP = 200 kPa

Figure 14: Pore water pressure generation at various fiber contents at CSR = 0.35 with a) CP = 50 kPa, b) CP = 100 kPa, c) CP = 200 kPa

Figure 15: Comparison of the effect of fiber type on liquefaction for CSR = 0.2 and CSR = 0.35; a) CP = 50, b) CP = 100, c) CP = 200

Figure 16: Cyclic stress ration versus number of cycles causing liquefaction for different confining pressure for a) Unreinforced sand, b) PP reinforced sand with fiber content of 0.50%

Figure 17: Axial strain time history for reinforced sand with PP fibers at CSR = 0.2 and CP = 200 kPa for different fiber contents; a) FC = 0.00%, b) FC = 0.25%, c) FC = 0.50%, d) FC = 1.00%

Figure 18: Axial strain time history for reinforced sand with PP fibers at CSR = 0.35 and CP = 50 kPa for different fiber contents; a) FC = 0.00%, b) FC = 0.25%, c) FC = 0.50%, d) FC = 1.00%
### Table 1: Summary of the characteristics of the test

| Fiber Type  | Fiber Content | CSR | Confining Pressure (kPa) | $N_t$ |
|-------------|---------------|-----|--------------------------|-------|
| Unreinforced | 0.0 %         | 0.2 | 50                       | 57    |
|             |               |     | 100                      | 36    |
|             |               |     | 200                      | 24    |
| PET* Fibers | 0.25 %        | 0.2 | 50                       | 68    |
|             |               |     | 100                      | 54    |
|             |               |     | 200                      | 43    |
|             |               | 0.35| 50                       | 8     |
|             |               |     | 100                      | 6     |
|             |               |     | 200                      | 5     |
|             | 0.50 %        | 0.2 | 50                       | 85    |
|             |               |     | 100                      | 63    |
|             |               |     | 200                      | 49    |
|             |               | 0.35| 50                       | 10    |
|             |               |     | 100                      | 8     |
|             |               |     | 200                      | 6     |
|             | 1.00 %        | 0.2 | 50                       | 115   |
|             |               |     | 100                      | 70    |
|             |               |     | 200                      | 64    |
|             |               | 0.35| 50                       | 18    |
|             |               |     | 100                      | 14    |
|             |               |     | 200                      | 9     |
| PP* Fibers  | 0.25 %        | 0.2 | 50                       | 63    |
|             |               |     | 100                      | 41    |
|             |               |     | 200                      | 32    |
|             |               | 0.35| 50                       | 8     |
|             |               |     | 100                      | 6     |
|             |               |     | 200                      | 4     |
|             | 0.50 %        | 0.2 | 50                       | 75    |
|             |               |     | 100                      | 75    |
|             |               |     | 200                      | 38    |
|             |               | 0.35| 50                       | 9     |
|             |               |     | 100                      | 7     |
|             |               |     | 200                      | 5     |
|             | 1.00 %        | 0.2 | 50                       | 103   |
|             |               |     | 100                      | 103   |
|             |               |     | 200                      | 52    |
|             |               | 0.35| 50                       | 13    |
|             |               |     | 100                      | 10    |
|             |               |     | 200                      | 7     |

* Number of cycles to reach the liquefaction

* Polyethylene terephthalate

* Polypropylene
Figures:

Figure 19: Grain size distribution of Babolsar sand
Figure 20: a) Waste bottle, b) Bottle chips, c) Showered down fibers, d) PET fibers in length of 15 mm
Figure 21: a) PP fibers, b) PP fibers in length of 15 mm
Figure 22: Cyclic triaxial apparatus
Figure 23: Reinforced sand with a) PET fibers, b) PP fibers
Figure 24: a) Control layers height by caliper, b) Specimen before triaxial cell assemblage, c) Specimen after saturation
Figure 25: a) Time history of axial strain, b) Time history of excess pore water pressure ratio, c) Time history of deviatory stress, for reinforced sand with PET fibers.
Figure 26: a) Time history of axial strain, b) Time history of excess pore water pressure ratio, c) Time history of deviatory stress, for reinforced sand with PET fibers
Figure 27: Number of cycles leading to liquefaction versus cyclic stress ratio at a) CP = 50 kPa, b) CP = 100 kPa, c) CP = 200 kPa
Figure 28: Number of cycles causing liquefaction versus at various confining pressure for reinforced sand with a) PET fibers b) PP fibers for CSR = 0.20.
Figure 29: Number of cycles causing liquefaction versus at various confining pressure for reinforced sand with a) PET fibers b) PP fibers for CSR = 0.35
Figure 30: Stress-Strain hysteresis for reinforced sand with different PET content at CP=100 kPa and CSR = 0.20
Figure 31: Pore water pressure generation at various fiber contents at CSR = 0.20 with a) CP = 50 kPa, b) CP = 100 kPa, c) CP = 200 kPa
Figure 32: Pore water pressure generation at various fiber contents at CSR = 0.35 with a) CP = 50 kPa, b) CP = 100 kPa, c) CP = 200 kPa
Figure 33: Comparison of the effect of fiber type on liquefaction for CSR = 0.2 and CSR = 0.35; a) CP = 50, b) CP = 100, c) CP = 200
Figure 34: Cyclic stress ratio versus number of cycles causing liquefaction for different confining pressure for a) Unreinforced sand, b) PP reinforced sand with fiber content of 0.50%
Figure 35: Axial strain time history for reinforced sand with PP fibers at CSR = 0.2 and CP = 200 kPa for different fiber contents; a) $FC = 0.00\%$, b) $FC = 0.25\%$, c) $FC = 0.50\%$, d) $FC = 1.00\%$. 
Figure 36: Axial strain time history for reinforced sand with PP fibers at CSR = 0.35 and CP = 50 kPa for different fiber contents; a) FC = 0.00%, b) FC = 0.25%, c) FC = 0.50%, d) FC = 1.00%