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Liquefaction potential of reinforced sand with plastic wastes

N. Jafari, R. Noorzad*, and B. Ta´negonbadi

Department of Geotechnical Engineering, Faculty of Civil Engineering, Babol Noshirvani University of Technology, Babol, Iran.

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Waste plastic fibers.

Abstract. Affected by the developed pore water pressure during undrained cyclic shear of saturated soils, granular soil liquefaction is regarded as a common phenomenon that occurs under earthquake loads. This phenomenon causes huge damage to infrastructure. Different reinforcement materials have been successfully implemented with particular attention to the use of waste materials to satisfy design specifications and mitigate the adverse environmental effects. This paper aims to investigate the possibility of using waste plastic fibers as reinforcement materials 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 Poly-Ethylene Terephthalate (PET) and Polypropylene (PP) fibers with the fiber contents of 0.25%, 0.5%, and 1% under the confining pressures of 50, 100, and 200 kPa at Cyclic Stress Ratios (CSR) of 0.2 and 0.35. The obtained results revealed that the addition of these waste plastic fibers could significantly increase the liquefaction resistance of Babolsar sand and that with an increase in the waste content, the number of cycles leading to liquefaction would increase. Addition of wastes decreased the pore water pressure generation, and this effect was more pronounced with an increase in the waste content.

1. Introduction

Since the horrible damages caused by liquefaction during the 1964 Niigata earthquake, many research studies have been performed on different properties of liquefaction [1]. Liquefaction is the most catastrophic form of geotechnical failure that is commonly triggered due to rapid development of Pore Water Pressure (PWP) and decrease in the effective Confining Pressure (CP) [1–4]. The liquefaction process usually converts the state of a soil element from solid into liquid [5] and causes significant damages 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].

Improvement of 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 for increasing the stability and strength of soil in different applications including embankments, retaining structures, slopes, foundations, and pavements [8,9]. Application of randomly distributed fiber for soil reinforcement was suggested in the early 1970s, and it quickly became the subject of many studies. Fibers are commonly

*. *Corresponding author. Tel.: +981135278377*
E-mail addresses: nazilajafari91@gmail.com (N. Jafari); rn0864@gmail.com, rnoorzad@nit.ac.ir (R. Noorzad); bahram.gonbadi@gmail.com (B. Ta'negonbadi)

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available in vast amounts in waste and natural forms [3,9]. Previous studies showed that using different types of fibers for soil reinforcement would increase the strength and bearing capacity of soils [10–13].

Over time, the population growth and widespread use of bottles and plastic materials have led to overproduction of these materials. Given that decomposition of these materials takes a long time, accumulation of these materials in the environment causes environmental problems [14–16]. Therefore, recycling and reuse of these plastic wastes have become two of the major challenges throughout the world. As some of these wastes are not biodegradable, they cause many environmental pollution problems to the surrounding environment [17]. Plastic waste is one of the most important municipal solid wastes due to an increase in sales and use of plastic packaging [18]. Currently, a great need is felt for determining a practical solution to disposal of waste plastics or reusing them as alternative materials 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 consequent repercussions on the environment [19]. Application of fibers in construction projects can attenuate 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, their reuse has received less attention in geotechnical projects [16]. However, some researchers have recently investigated the possible applications of fibers in soils and other materials such as mine tailings and coal ashes [9].

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

Initial liquefaction can be defined as the state where the pore pressure is close to the initial CP. In other words, this state occurs when the excess PWP ratio reaches 1.0. In this case, an increase in the axial strain becomes substantial. This phenomenon is primarily observed in loose sands. The second type of liquefaction, known as the limited liquefaction or cyclic mobility, happens in medium-dense to dense sand types. Given that achievement of zero effective stress was impermanent in such soil types, the following softening was temporary; therefore, it did not lead to collapse. Instead, as loading progressed, the specimen recovered its stiffness and strength owing to dilation. This state was largely defined by occurrence of about 5% Double Amplitude Axial Strain (DAAS) or development of l00% excess PWP ratio. Once the 100% excess PWP ratio is developed, large (not drastic) strain accumulation (not strain softening) occurs in every loading cycle. However, deformation, thereafter, did not increase indefinitely and complete loss of strength did not take place in the sample even after the onset of initial liquefaction [20–24]. In contrast, Ishihara (1993) defined cyclic instability as follows: "Nonetheless, 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% PWP 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 undergoes a drastic 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, the strain accumulation becomes drastic (or even continue without imposing any additional loading and for this reason, it is referred to as flow liquefaction), and the sample becomes fully liquefied (like liquid) within few loading cycles. This phenomenon is commonly observed for loose saturated granular soils [21–24]. The main difference between the initial and limited liquefaction is that in the limited liquefaction, complete loss of strength does not take place. In silty sands or sandy silts containing some fines, the PWP does not fully develop, but it stops building up from reaching about 90%–95% of the initial confining stress. However, a sizeable amount of cyclic strain is observed to be developing, indicating considerable softening of these soils [21–24]. As a result, occurrence of 5% DA axial strain in the cyclic triaxial test is taken into consideration below as a criterion to coherently define the state of cyclic softening or liquefaction of soils from clean to fine-containing sands. When subjected to cyclic loading, clayey cohesive soils do not usually lose complete strength even under saturated conditions. The behavior of any clayey material is characterized by strength degradation with the number of cycles and accumulated strain [25].

2. Background

Utilization of tensile elements to improve the soil strength dates back to 3000 years ago, when Iranians as well as Babylonians used a combination of straw and soil as a building material [26]. Over the past decades, the field and laboratory studies have revealed that use of waste, synthetic, and natural fibers as the tensile components would lead to significant improvement and adjustment in the mechanical properties such as compressibility, stiffness, strength, and permeability of soils [9,10]. In this regard, different mitigation methods have been successfully established to reduce the liquefaction potential and its subsequent effects [27]. Vercueil et al. [28] and Altun et al. [6] studied liquefaction of the reinforced sand based on geosynthetics. They found that the resistance of sand deposits to liquefaction could be considerably enhanced with geosynthetic reinforcement [28]. In addition, the application of conventional reinforcing techniques such as geogrid and geotextile reinforced earth that use randomly distributed fibers as the reinforcement materials has gained greater popularity because of their acceptable performance [2,29].

Many studies have been carried out to date to evaluate the effects of fiber inclusion on the liquefaction potential of the reinforced soils. Noorzad and Amini [2] studied the liquefaction and shear modulus of reinforced Babolsar sand with Polypropylene (PP) fibers under a cyclic triaxial loading with different CP. They concluded that the confining stress had a significant effect on degrading liquefaction potential and that the addition of fibers appreciably increased the shear modulus and liquefaction resistance of sands [2]. Other researchers also reported similar observations, indicating that fibers were found to improve the shear modulus and liquefaction resistance of soils [30–33]. Dahal [27] conducted a laboratory research on the shear parameters and liquefaction potential of the reinforced sand using PP fibers. The obtained results revealed that the reinforced samples did not exhibit initial liquefaction compared to unreinforced samples; however, their resistance to liquefaction increased with the introduction of fibers [27]. Eskisar et al. [29] pointed out the direct relationship between the number of loading cycles and generation of excess PWP in reinforced sands. Krishnaswamy and Thomas Isaac [5] did several triaxial tests to assess the liquefaction potential of the reinforced sands using geotextile, including coir as well as woven and nonwoven fibers. The results showed that reinforcement could significantly increase the liquefaction resistance of the sand under study [5]. Furthermore, they studied the effect of the size of samples considering different sample sizes and found that larger specimens were characterized by more resistance to liquefaction than smaller ones [5]. Hence, it is rational to lean on the results of smaller samples to evaluate the reinforced sand liquefaction potential.

Benson and Khire [34] examined the behavior of reinforced soils using strips of reclaimed High-Density Polyethylene (HDPE). Their results indicated enhanced strength and resistance to deformation of the sample under study, which depended on the aspect proportion (or length) of the strips [34]. Babu and Chouksey [35] highlighted that inclusion of plastic waste fibers improved the soil resistance and reduced its compressibility. This can be beneficially used in settlement reduction and improvement of the bearing capacity in the design of shallow foundations [35]. Meddah and Merzoug [36] evaluated the shear strength properties of the sand reinforced by rubber fibers in the dense and loose states with fiber percentages of 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, and 2% of the sand dry weight. According to their results, the rubber fibers used in the dune sand not only represented an environmentally-friendly method but also improved the peak strength, residual strengths, and characteristics of shear strength, thus making the mechanical behavior of sand more ductile [36]. Banerjee et al. [37] studied the liquefaction potential of cohesionless soils under a near-saturated condition through a series of cyclic triaxial tests on the consolidated undrained specimen. To this end, several tests were carried out with different ratios of cyclic deviator stress to the initial Confining Stress (CSR) ranging from 0.15 to 0.35. They concluded that the failure mechanism in all specimens, which were moderately dense cohesionless soils, corresponding to cyclic mobility. In addition, they remarked that the soil specimen in the near-saturated condition required higher CSR and/or higher number of load cycles to liquefy.

Keramatikerman et al. [38] conducted a series of cyclic triaxial tests on the fly ash stabilized sand to assess the liquefaction resistance of stabilized sand with fly ash under cyclic loading. They also evaluated the effects of the relative density (Dr of 20% to 80%), FA content (2% to 6%), different CP (50 kPa to 90 kPa), and curing time liquefaction resistance (0 to 28 days). Results revealed that at constant relative density and different CP, specimens with higher FA content exhibited greater liquefaction resistance than others. In addition, they demonstrated that the specimen curing decreased the liquefaction potential.

Liu [39] carried out a large number of cyclic triaxial tests to evaluate the impact of fine contents on the soil liquefaction resistance. A total of 96 cyclic triaxial tests on the uniform medium Monterey sand with six different percentages of fine content as well as 198 cyclic triaxial tests on the uniform medium concrete sand with five different percentages of fine content were carried out. In these tests, the effects of different relative densities (Dr of 30% to 60%), different CP (from 103 kPa to 207 kPa), and six different stress ratios (ranging from 0.2 to 0.45) were investigated. The findings showed that addition of fine contents up to 12% in clean sand might cause an increase in the liquefaction tendency while once the percentage of the fine content exceeded 20%, the liquefaction resistance would increase.

Despite the fact that a majority of the previous studies on the reinforced soils with plastic waste have focused on the shear strength and deformation characteristics under static loading, the available information on the impact of plastic wastes on the liquefaction potential of sand under dynamic loading is quite limited. In this regard, the current study aimed to provide adequate technical data on the cyclic triaxial behavior of sand reinforced with waste Poly-Ethylene Terephthalate (PET) and PP fibers with the dry sand weights of 0.25, 0.5, and 1%. In particular, the effect of waste fibers on the liquefaction potential and PWP generation for samples was investigated 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 sand collected from Babolsar, Iran with the specific gravity of 2.74 (based on ASTM D854-14 [40]) at 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). The mean grain size (D_{50}) of the tested sand was calculated as 0.17 mm, and the curvature and uniformity coefficients were obtained as 1.3 and 1.8, respectively. Figure 1 shows the grain size distribution curve of Babolsar sand obtained through ASTM D422-63 [44].

3.1.2. PET fibers

PET is a lightweight and crystal material that is also the most common polymer resin of the polyester family. Characterized by a density of 1.34 g/cm^3, it can be transformed into a plastic state at a temperature higher than 72°C [16]. In order to produce PET fibers, first, the waste bottles were ground into bottle chips and then, heated by well-equipped machines under a controlled condition to produce PET fibers. In this study, the length of the fibers was selected equal to 15 mm, and the specimens were prepared with the fiber content containing the dry sand weights of 0.25%, 0.5%, and 1%. Figure 2 presents an overview of the production procedure of these fibers.

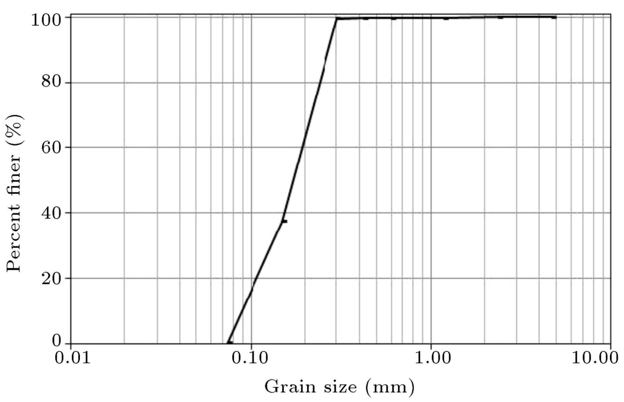

Figure 1. Grain size distribution of Babolsar sand.

3.1.3. Sack PP fibers

Sack PP plastic is resistant to acidic and alkaline environments and is characterized by acceptable tensile strength. PP plastic used in this study was obtained from the waste materials of a gunny production plant. The density and melting temperature of this plastic were measured as 0.9 g/cm^3 and 170°C, respectively. In this research, discrete PP fibers were manufactured by cutting the plastic wastes into smaller parts of 15 mm in length and approximately 2–2.5 mm in width. In the current research, the PP fibers were selected with different contents including different soil dry weight percentages of 0.25%, 0.5%, and 1%. Figure 3 presents an overview of these fibers.

3.2. Test equipment

Throughout the research process, the stress-controlled cyclic triaxial tests were conducted using an MTM Global apparatus. Figure 4 shows an overall view of cyclic triaxial apparatus.

The board was employed 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 monitor the pressure and suction values. In addition, three graduated burettes were included on the board in order to monitor Top Back Pressure (TBP) and Bottom Back Pressure (BBP) to provide the required water. Upon using these burettes, the amount of input and output water of the sample can be determined. In order to control the amount of input and output water, two valves were installed on the board. Moreover, the electrical sensors were provided to determine the water pressure and control the valve to set the cell pressure. The sensors can precisely operate in the range of zero to 1000 kPa [16].

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

3.3. Sample preparation

Previous studies have confirmed the considerable effect of the sample preparation method on the behavior of the reinforced soil [45]. In this research, cylindrical

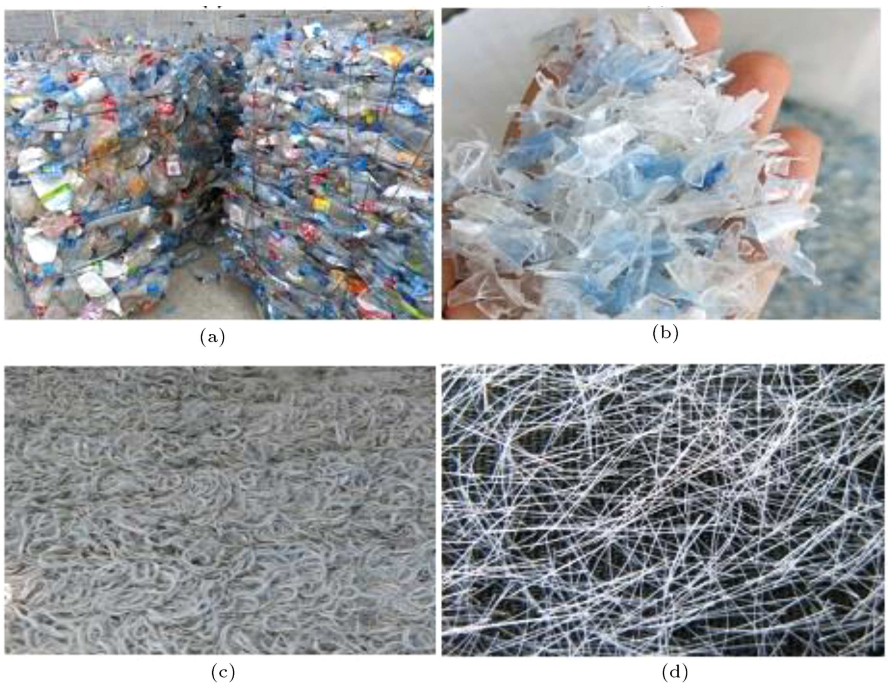

Figure 2. (a) Waste bottle, (b) bottle chips, (c) showered down fibers, and (d) PET fibers in length of 15 mm.

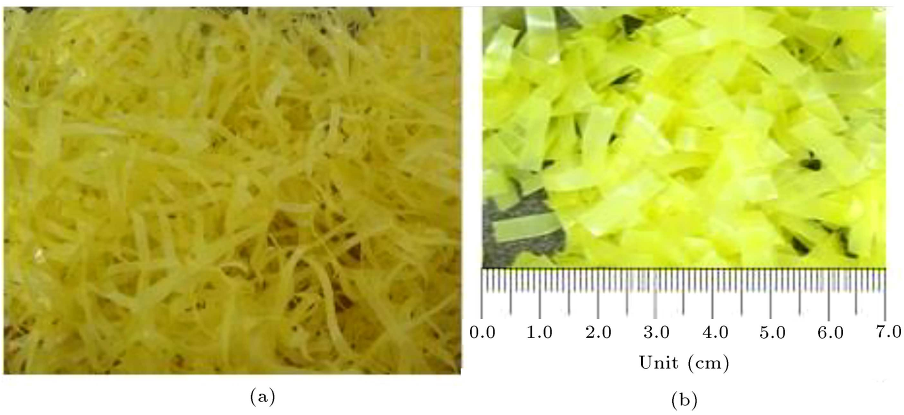

Figure 3. (a) PP fibers and (b) PP fibers in length of 15 mm.

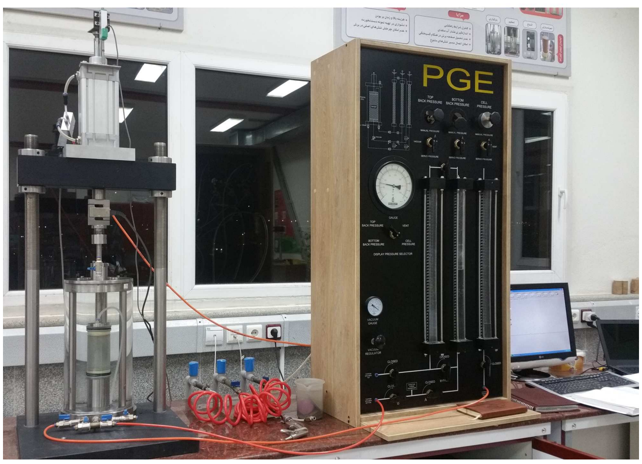

Figure 4. Cyclic triaxial apparatus.

samples that are 50 mm in diameter and 100 mm in height were prepared using moist tamping method in five equal layers to achieve relative density of 40% for specimen before consolidation, being equal to 1.57 g/cm^3 of sand mixtures in dry unit weight.

In order to evaluate the efficiency of the sample preparation methods, different methods including wet/moist tamping, air pluviation, water sedimentation, and under-compaction techniques, to name a few, were examined in the laboratory, and the homogeneity of samples was evaluated. Finally, a moist tamping method was chosen to prepare the samples using under-compaction technique, as proposed by Ladd [46]. This technique is usually used for preparing the fiber-reinforced sand in laboratories facilitating the density control of samples and segregation prevention [45,47].

(a) (b)

Figure 5. Reinforced sand with (a) PET fibers and (b) PP fibers.

(a) (b) (c)

Figure 6. (a) Control layers height by caliper, (b) specimen before triaxial cell assemblage, and (c) specimen after saturation.

Moreover, this method simulates the in-situ condition almost accurately [47]. It is suggested that water be added to sand to achieve a better mixture of sand and fiber such that they do not float [2]. To determine the needed amount of water for preparation of the samples, different water contents including 5%, 10%, and 15% were considered, and the homogeneity of samples was evaluated. According to the results, 10% water content was determined as the optimum moisture content to prepare the sand-fiber mixtures.

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

3.4. Test procedure

In this research, 42 cyclic triaxial tests were done on reinforced sands collected from Babolsar, Iran based on ASTM-D5311 provisions [48]. The detailed experimental program is presented in Table 1. Followed by preparing the specimen in the apparatus mold and prior to the mold disassembly, 10 kPa vacuum was applied to stabilize the specimen (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 remove the applied vacuum pressure without manipulating the relative density of the specimen. This, in turn, provides an isotropic CP 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 easier in water than in air, the saturation process becomes simpler. Next, distilled de-aired water is permeated from the base to the cap of the specimen with a low pressure until the total amount of passed water from the sample became more than two times the initial volume of the specimen. Of note, use of de-aired water decreased the time and backpressure required for saturation. Subsequently, cell pressure and back pressure increased step by step with sufficient time between increments to facilitate equalization of water pore pressure throughout the sample. It should be noted that the difference between the back and cell pressures was kept almost constant at 10 kPa to avoid consolidation of the specimen during the saturating process.

The sample saturation continued until the B value [16] reached 0.95 or higher. Figure 6(c) provides an overview of the sample after the saturation process. To consolidate the samples isotopically, the cell pressure increased at a constant back pressure of 300 kPa until the difference between the cell and back pressures reached the value of the desired effective CP, which was selected as 50, 100, and 200 kPa in this study.

Two-way stress-controlled cyclic loading tests were carried out on the unreinforced and reinforced consolidated specimens under an undrained condition with a loading frequency of 1 HZ. The cyclic stress ratios (CSR $= qcyc/2\sigma'_3$) of 0.2 and 0.35 were considered in simulating medium and severe earthquakes that are relevant in the studied region. Axial loading, axial strain, and excess PWP were measured at the intervals of 0.001 s, and the test results for different samples were analyzed based on these obtained values. Based on the relative density of the loose-medium sand samples, the expected liquefaction scenario for unreinforced samples was initial liquefaction while for the reinforced samples with both PP and PET fibers, the cyclic mobility was expected. Liquefaction occurred in this study where the DAAS value over the cyclic loading reached 5% [48].

4. Results and discussion

Figures 7 and 8 show the axial strain time history, ratio of excess water pore pressure, and applied deviator stress for reinforced sand with PET fibers having CSR values of 0.2 and 0.35, respectively. As observed in Figures 7(a) and 8(a), the application of constant cyclic deviator stress gradually increased the axial strain until the DAAS of 5% (liquefaction criterion) was reached. The ratio of excess water pore pressure that was also regarded as the ratio of the developed excess water pore pressure to the effective confining stress ($r_u = \Delta U/\sigma'_3$) [48] increased gradually with time. Figures 7(b) and 8(b) show the development of r_u for these two samples.

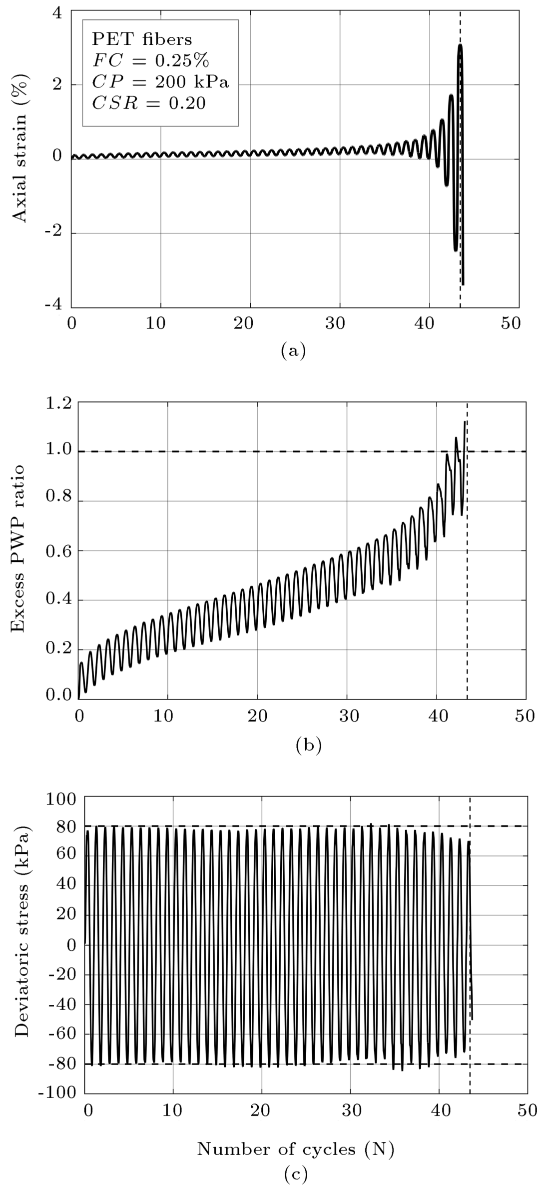

Figure 7. (a) Time history of axial strain, (b) time history of excess pore water pressure ratio, and (c) time history of deviatory stress for sand reinforced with PET fibers.

Table 1. Summary of the characteristics of the test.

Fiber type	Fiber content	CSR	Confining pressure (kPa)	N_L^*
Unreinforced	0.0%	0.2	50	57
			100	36
			200	24
		0.35	50	7
			100	4
			200	3
PET$^{\times}$ 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	46
			200	38
		0.35	50	9
			100	7
			200	5
	1.00%	0.2	50	103
			100	65
			200	52
		0.35	50	13
			100	10
			200	7

Note: *: Number of cycles to reach the liquefaction; $^{\times}$: Polyethylene terephthalate; $^{■}$: Polypropylene.

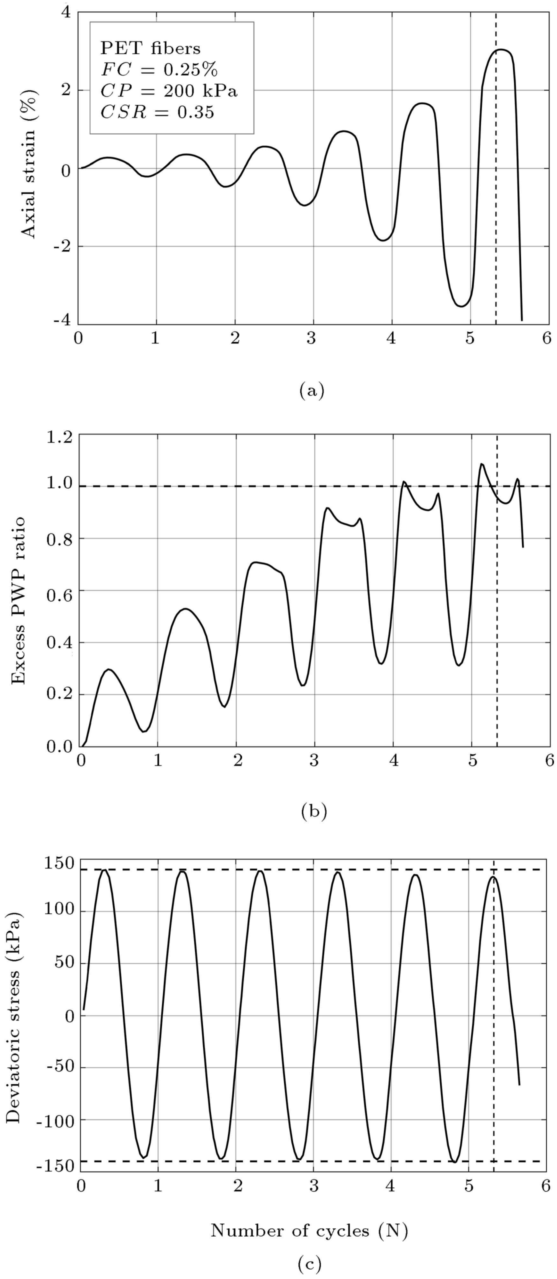

Figure 8. (a) Time history of axial strain, (b) time history of excess pore water pressure ratio, and (c) time history of deviatory stress for reinforced sand with PET fibers.

As observed, the generated r_u in the specimen was periodically changed during the cyclic loading, while its value increased in each loading cycle in a cumulative manner. As observed, both specimens reached their initial liquefaction ($r_u = 1$) before failure while the unreinforced sand reached its initial liquefaction and failure at the same time. More details about this issue are given below.

4.1. Effects of fiber content

Figure 9 shows the resistance of the reinforced Babolsar sand to liquefaction according to the relation between the CSR and relating numbers of the required cycles to lead liquefaction (DAAS of 5%) for both types of used fibers and their different contents. As obviously observed in this figure, the resistance of Babolsar sand to liquefaction in both types of plastic wastes was improved upon increasing the fiber content.

Figures 10 and 11 show the variations in the required number of cycles to reach liquefaction against the waste fibers content for the reinforced samples at different CP. It can be concluded from these figures that soil reinforcement (with both types of plastic wastes) had a considerable effect on decreasing the liquefaction potential. To be specific, the number of cycles leading to liquefaction varied from 57 for the unreinforced sand to 115 for the 1% PET reinforced sample at a CP of 50 kPa and CSR of 0.2. The corresponding values at the CSR of 0.35 and for 1% PP reinforced sample are 7 and 13, respectively. In fact, the resistance of the reinforced sand to liquefaction increased upon increasing the fiber content, which was inconsistent with the behavior in the previous researchers [3,6,27,30–33] mainly because use of plastic waste fibers as reinforcement materials can enhance interlocking of soil particles, leading to uniform distribution of PWP within the samples. Since the plastic waste-reinforced sand is subject to deformation, the friction appearing between the soil and plastic wastes can develop the tensile stress in the plastic wastes, leading to an increase in sample confinement as a result of which the freedom of movement of sand grains is reduced. Consequently, less PWP is developed due to the cyclic loading on the sample. Finally, this factor significantly improves the liquefaction resistance of the reinforced sample, compared to that of the unreinforced one. Boominathan and Hari [30] and Noorany and Uzdavines [33] also reported some improvement in the liquefaction potential of the fly ash and sand due to the use of mesh/fiber components.

Figure 12(a)–(d) shows the stress-strain curve (hysteresis loops) for the PET-reinforced sand with different fiber contents under a confining stress of 100 kPa and CSR of 0.2. Evidently, unreinforced sand exhibited a sudden growth in the axial strain and reached a DAAS of 5% (liquefaction criterion) in fewer cycles (36 cycles). In the case of the reinforced sand, however, a gradual increase in the axial strain against the applied cyclic loading was observed, and the required number of cycles to attain the liquefaction criterion also increased. This behavior was more noticeable with the accumulation of the fiber content (i.e., for 1% PET reinforced sample, 74 cycles are required to reach liquefaction). Furthermore, reinforced samples indicate an inelastic behavior, and the mean slope of the loops decreased from cycle to cycle, indicating stiffness degradation of these samples during the cyclic loading.

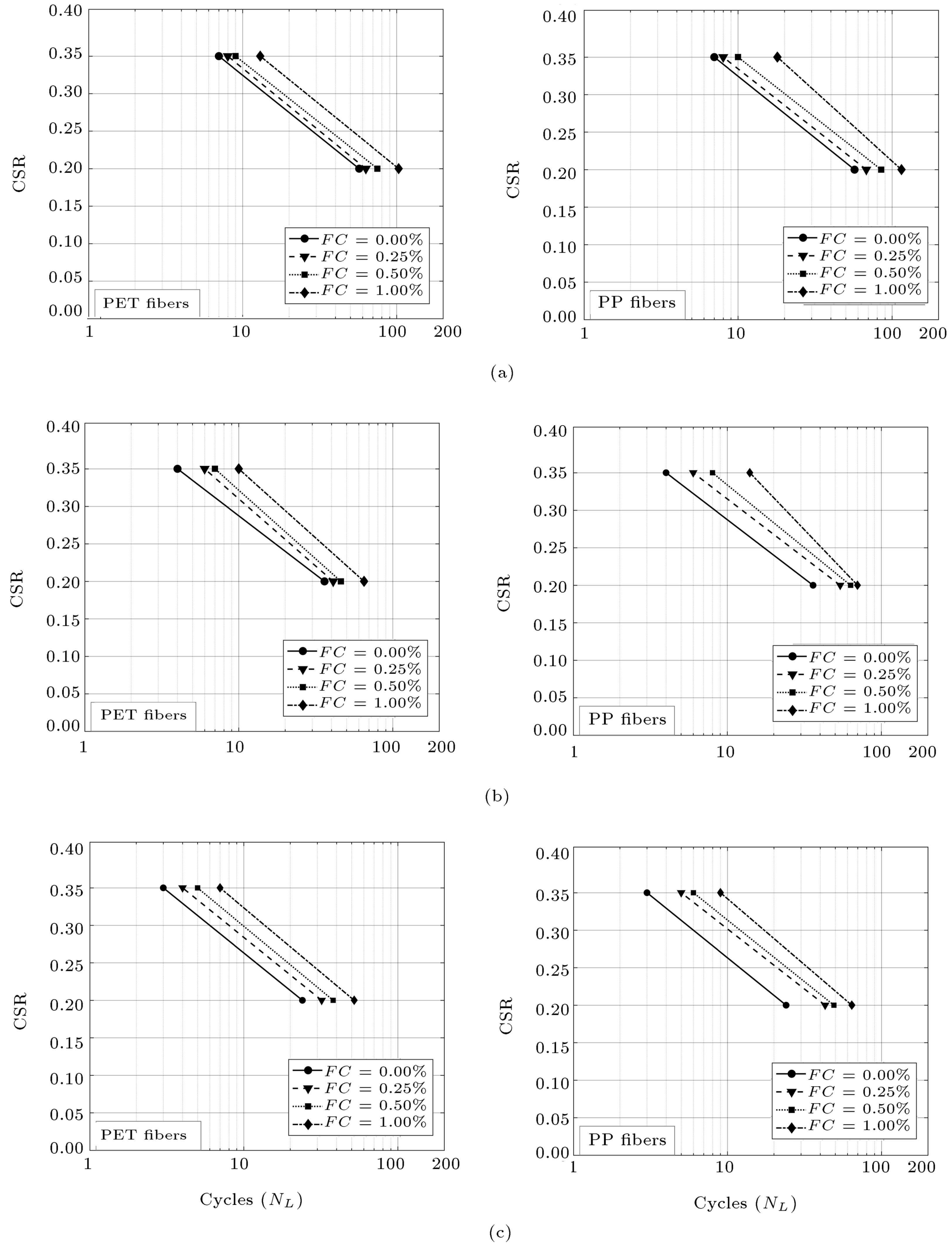

Figure 9. Number of cycles leading to liquefaction versus cyclic stress ratio at (a) $CP = 50$ kPa, (b) $CP = 100$ kPa, and (c) $CP = 200$ kPa.

The development of excess PWP ratio (r_u) for both unreinforced and reinforced (containing the two types of plastic wastes) types of sand at different CP and CSR value of 0.2 is depicted in Figure 13(a)–(c). As observed from this 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 the applied cyclic loading. On the contrary, the mentioned rate in the reinforced sand (with both two types of plastic wastes) is significantly reduced, and the initial liquefaction state is reached in more cycles. It can also be concluded that inclusion of fibers in the sand delays its initial liquefaction state due to the sand dilation, which in turn causes decrement in the PWP throughout the specimen. Noorzad and Fardad Amini [2] and Maheshwari at al. [7] reported the same results for reinforced sand with other types of fibers. In addition, the excess PWP in the initial cycles of loading increased rapidly and the effect of fiber inclusion was negligible. In fact, fiber presence was ineffective at

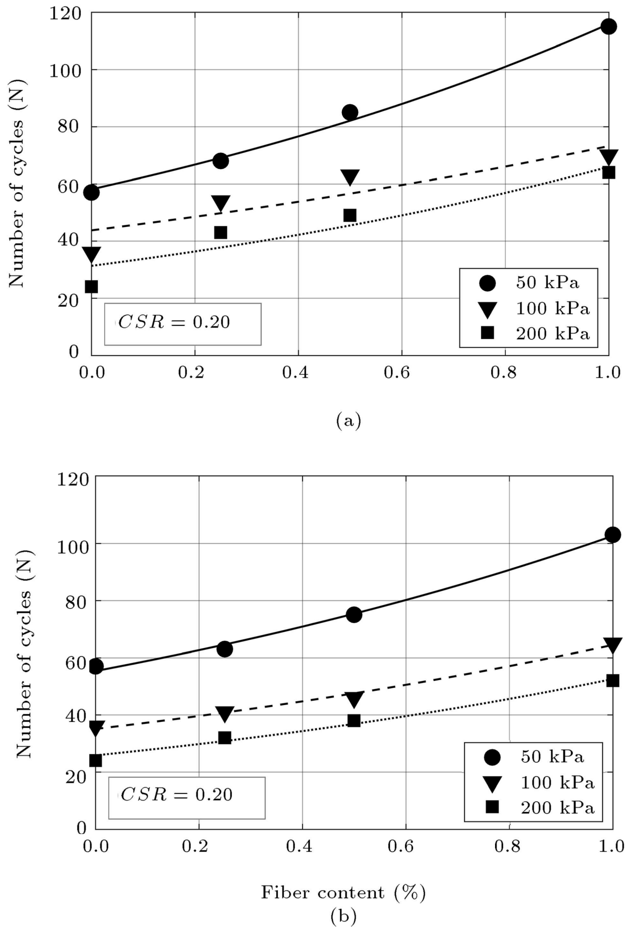

Figure 10. Number of cycles causing liquefaction versus those at various confining pressures for reinforced sand with (a) PET fibers and (b) PP fibers for $CSR = 0.20$.

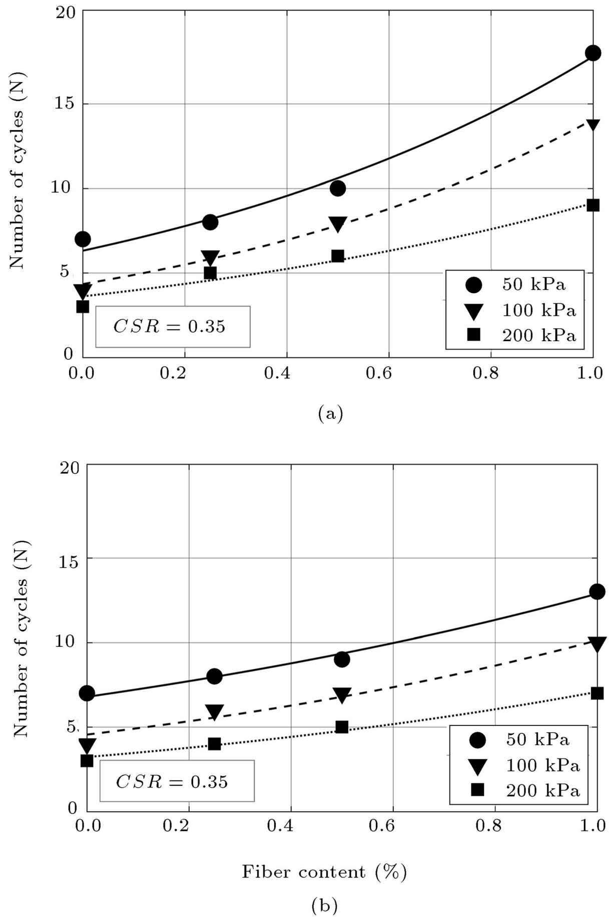

Figure 11. Number of cycles causing liquefaction versus those at various confining pressures for reinforced sand with (a) PET fibers and (b) PP fibers for $CSR = 0.35$.

values of r_u lower than 0.2 mainly because during the first cycles, the strain level as well as the deformation were low and as a result, the required extension to engage fibers in tension was not met. Hence, addition of 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 the reinforced sand with PP fibers at a CP of 100 kPa in specimens with $r_u < 0.5$ was greater than that with $r_u > 0.5$.

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

4.2. Effects of fiber type

This study utilized two types of monofilament plastic wastes with a length of 15 mm: the PET fibers with a negligible thickness and PP fibers in the form of 2–2.5 mm wide narrow strips (as shown in Figure 5). Figure 15 makes a comparison of the results from the tests carried out on the PET reinforced sand and those from the PP reinforced sand with different CSR values. As observed, at both CSR values, the PET fibers were found more effective in increasing their resistance to liquefaction and controlling the development of PWP of the reinforced sand, compared to the PP fibers.

As previously discussed, a homogeneous mixture is one of the prerequisites to obtaining reliable results. Use of both PET and PP fibers in the sand results in homogeneous mixtures. In comparison to PP fibers, the PET fiber possesses a greater surface area which reduces the slippage potential of fibers, thus ensuring the greater improvement of the liquefaction resistance of the PET-reinforced sand than that of the PP-reinforced one.

4.3. Effects of CP

According to Figures 10 and 11, at a certain fiber percentage, the number of cycles leading to liquefaction will decrease upon increasing the CP. This finding is

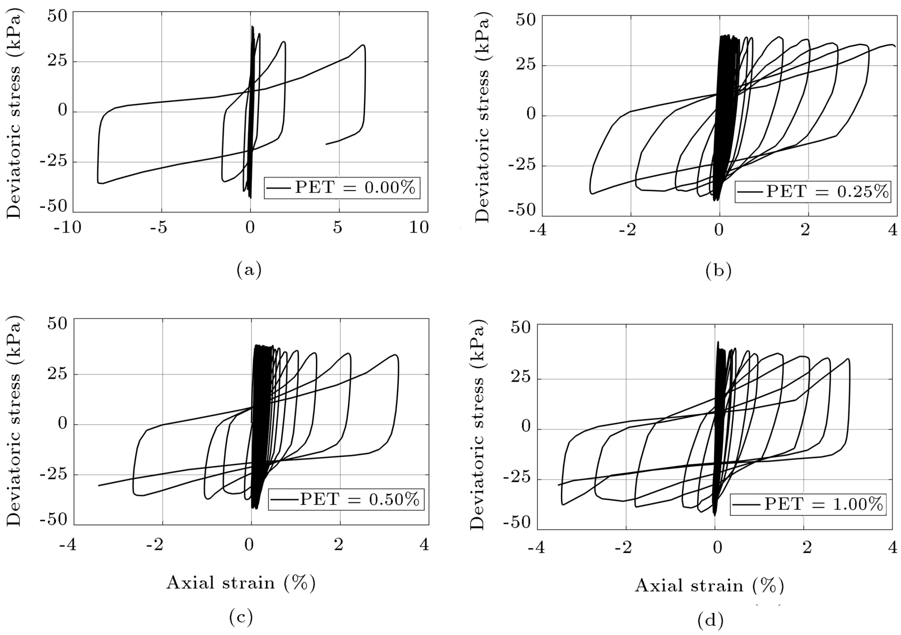

Figure 12. Stress-strain hysteresis for reinforced sand with different PET contents at $CP = 100$ kPa and $CSR = 0.20$.

contrary to the previously reported results obtained by Noorzad and Fardad Amini [2]. The main reason for this discrepancy can be attributed to the remaining constant of CSR in this research while increasing the CP. According to the definition of CSR, in order to keep its value constant, the amount of the applied shear to the sample increased upon increasing the CP, which in turn reduced the number of cycles leading to liquefaction.

Figure 16 presents the relation between the CSR and related number of the required cycles leading to liquefaction at different CP values in both unreinforced and PP-reinforced sands with a fiber content of 0.5% to better elaborate the impact of the CP. As observed in this figure, the impact of the confining stress under a moderate loading (CSR value of 0.2) is more considerable in the liquefaction resistance of the reinforced sand than that in the sever loading (CSR value of 0.35). In addition, variation in the magnitude of the deviatory stress (CSR value) has less effect on the soil liquefaction resistance of deep soils at high CP than the surface soils at low CP.

4.4. Cyclic mobility

Instability under cyclic loading is discovered to be caused by cumulative development of the 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 sands at CSR values of 0.2 and 0.35 is depicted in Figures 17 and 18, respectively. As is observed, the unreinforced specimens suddenly reached the DAAS of 5% as indication of liquefaction. On the other hand, inclusion of plastic waste fibers caused cyclic mobility in the specimens, leading to gradual increase in strain until failure. For example, at the CSR of 0.2, the PP-reinforced sample with a fiber content of 1% (Figure 17(d)) reached the failure criteria in 52 cycles, while this value for the unreinforced one (Figure 17(a)) was 23 in cycle numbers. This outcome shows that fiber inclusion in the sand enhanced its cyclic behavior. 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 upon increasing fiber content.

5. Summary and conclusions

This paper investigated the effect of adding waste Poly-Ethylene Terephthalate (PET) fibers and Polypropylene (PP) fibers on liquefaction resistance and Pore Water Pressure (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 conditions. 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 changed from 57 for the unreinforced sand to 115 for the 1% PET reinforced sample at a confining pressure of 50 kPa and Cyclic Stress Ratios (CSR) of 0.2. This effect was due to the fact that use of fibers as reinforcement materials improved the interlocking between soil particles;

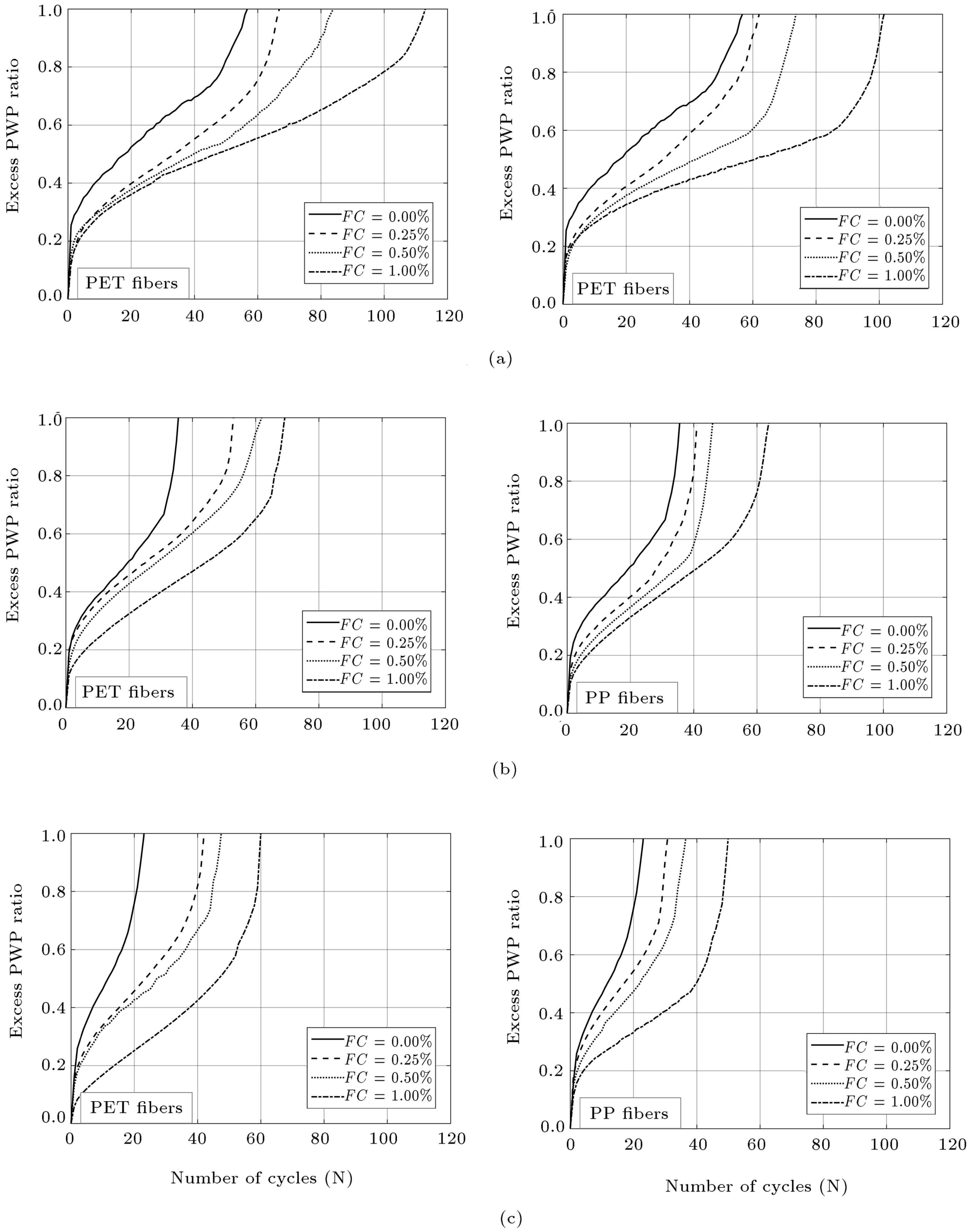

Figure 13. Pore water pressure generation at various fiber contents at $CSR = 0.20$ with (a) $CP = 50$ kPa, (b) $CP = 100$ kPa, and (c) $CP = 200$ kPa.

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

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

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

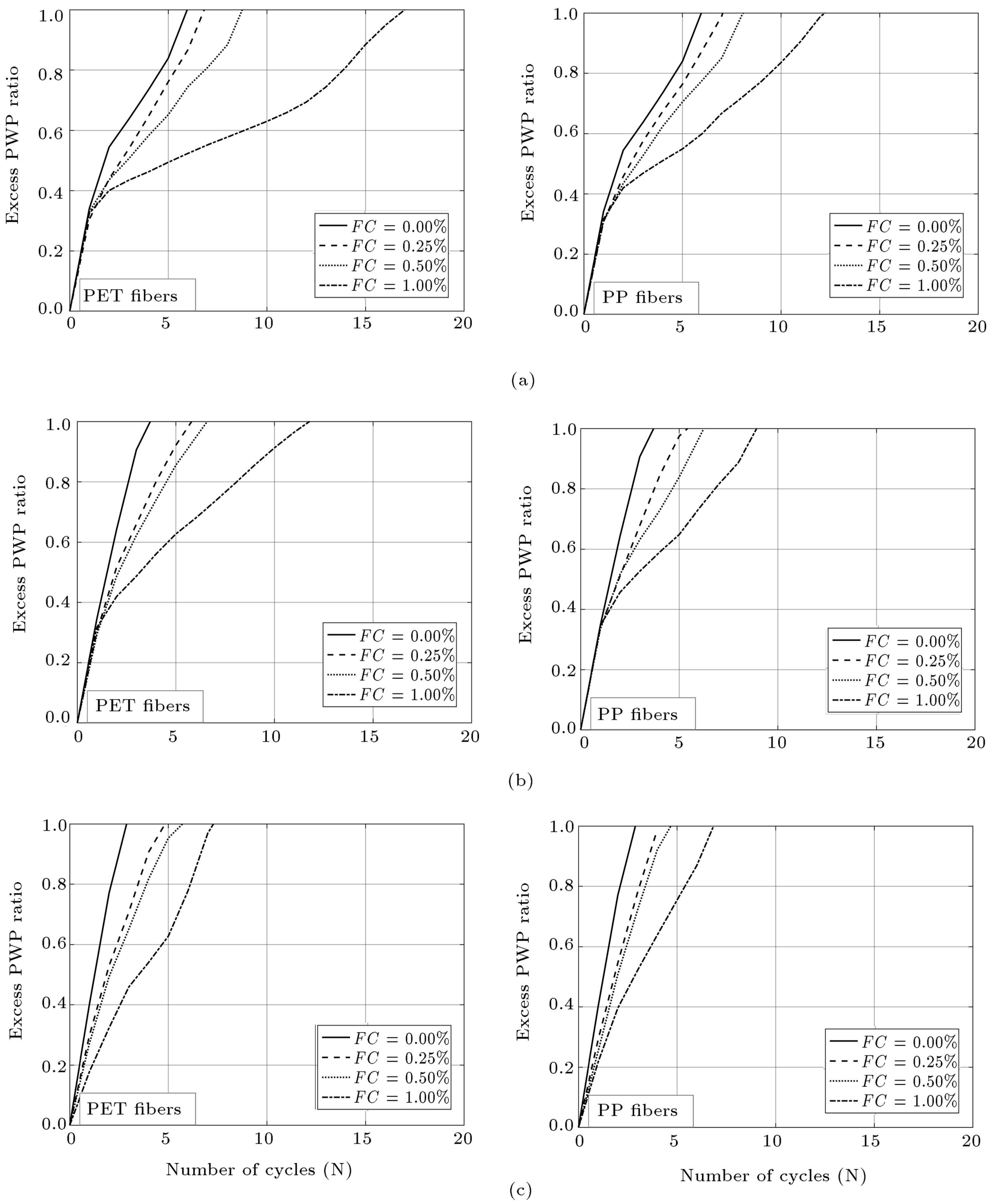

Figure 14. Pore water pressure generation at various fiber contents at $CSR = 0.35$ with (a) $CP = 50$ kPa, (b) $CP = 100$ kPa, and (c) $CP = 200$ kPa.

and sand particles, the impact of fiber inclusion on the progress of PWP in initial cycles was more apparent;

- The unreinforced specimens were 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. Of note, the cyclic mobility was specified upon reaching the 5% Double Amplitude Axial Strain (DAAS);
- Under high deviatory stress, the role of confining stress was more considerable in improving the liquefaction resistance of the reinforced sand. The variation in the deviatory stress magnitude had less effect on liquefaction resistance of soils with a high confining pressure (deep soil conditions) than the soils with low confining pressure (surface soil condition).

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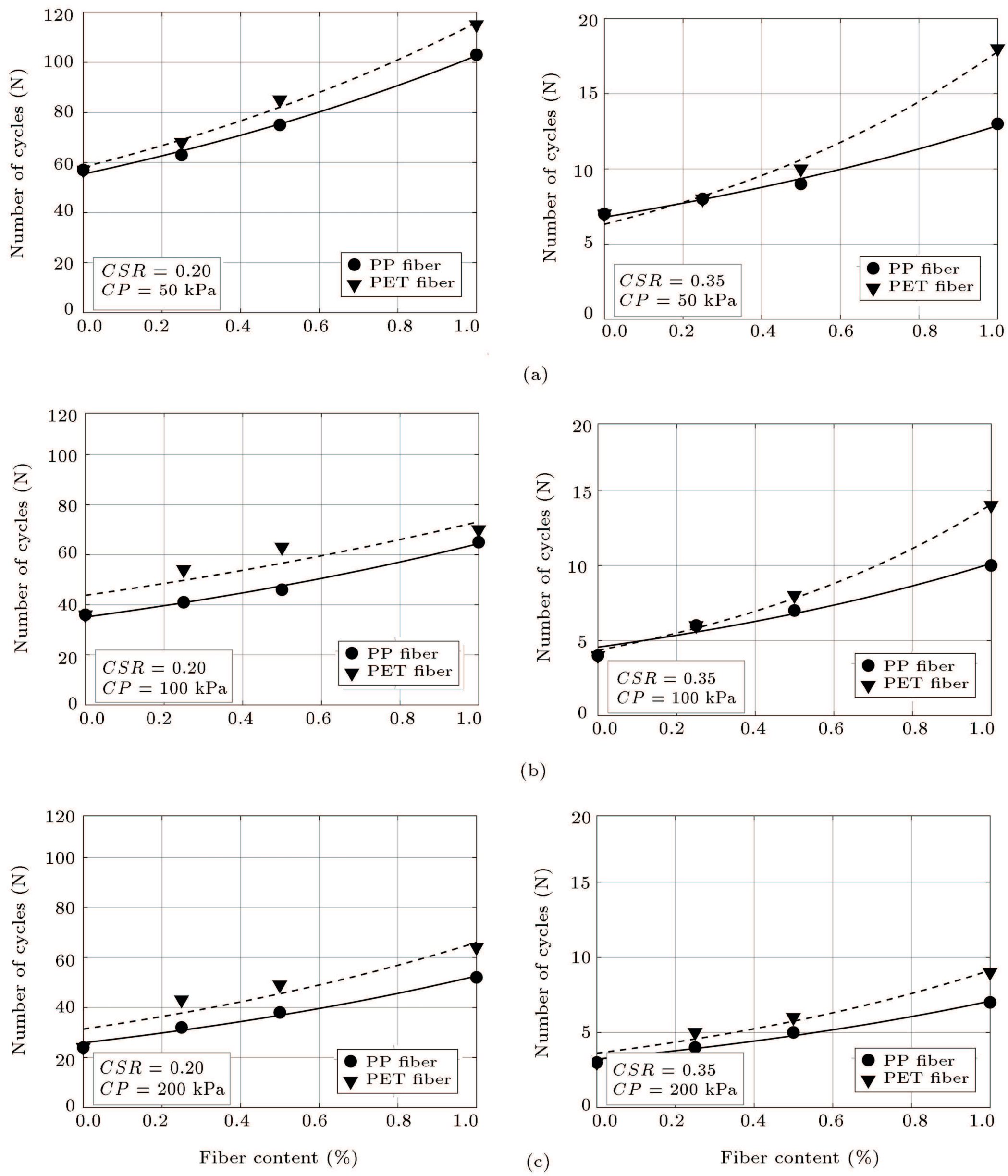

Figure 15. Comparison of the effect of fiber type on liquefaction for $CSR = 0.2$ and $CSR = 0.35$: (a) $CP = 50$ kPa, (b) $CP = 100$ kPa, and (c) $CP = 200$ kPa.

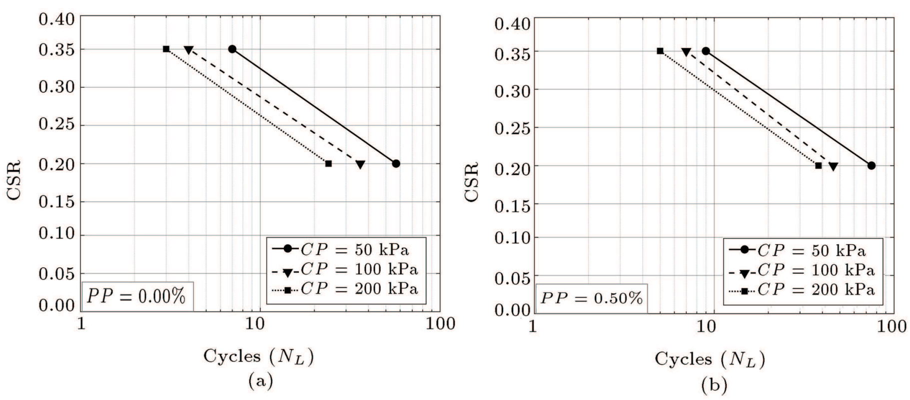

Figure 16. Cyclic stress ration versus number of cycles causing liquefaction for different confining pressures for (a) unreinforced sand and (b) PP reinforced sand with fiber content of 0.50%.

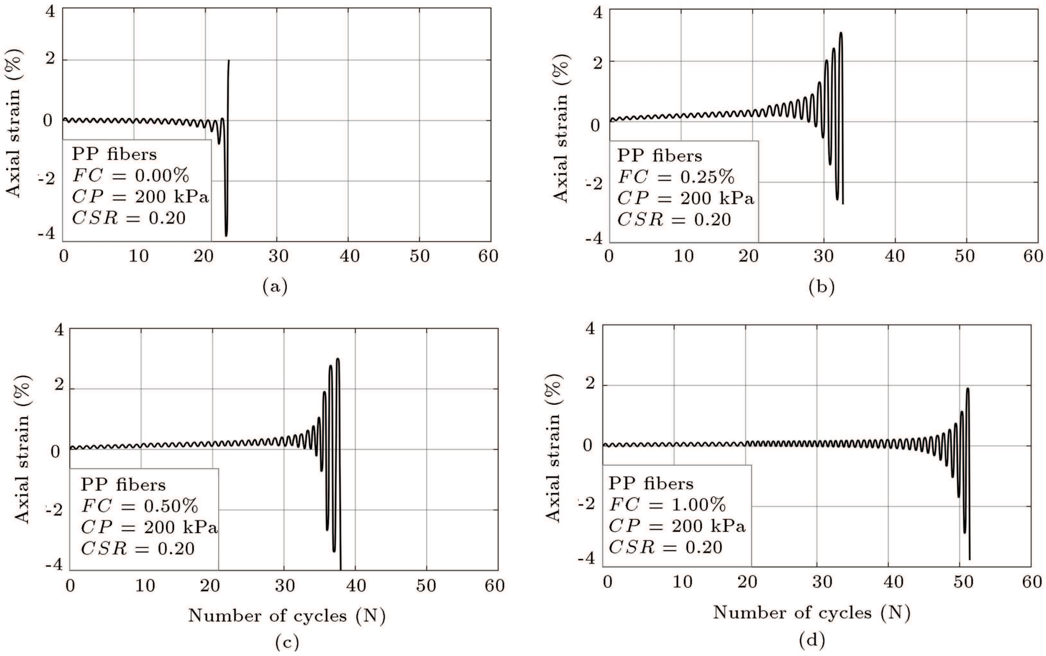

Figure 17. Axial strain time history for reinforced sand with PP fibers at $CSR = 0.2$ and $CP = 200$ kPa for different fiber contents: (a) $FC = 0.00\%$, (b) $FC = 0.25\%$, (c) $FC = 0.50\%$, and (d) $FC = 1.00\%$.

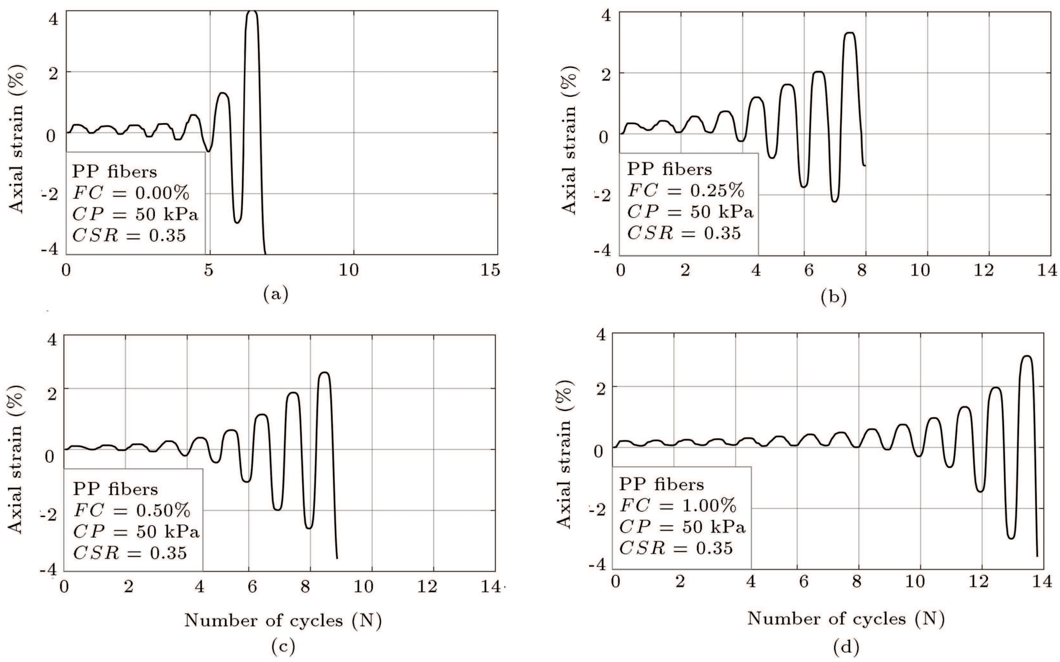

Figure 18. Axial strain time history for reinforced sand with PP fibers at $CSR = 0.35$ and $CP = 50$ kPa for different fiber contents: (a) $FC = 0.00\%$, (b) $FC = 0.25\%$, (c) $FC = 0.50\%$, and (d) $FC = 1.00\%$.

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Biographies

Nazila Jafari was born in Sari, Mazandaran, Iran in 1991. She received her BSc degree in Civil Engineering in 2013 and her MSc degree in Geotechnical Engineering in 2016, both from Babol Noshirvani University of Technology, Babol, Iran. Her master's thesis is entitled "Investigation of Liquefaction of Babolsar Sand Mixed with Plastic Waste" defended at Babol Noshirvani University of Technology under the supervision of Prof. Reza Noorzad. After graduation, she started working at Baran Geotechnics as an R&D manager in 2017. Her current research interests include, but not limited to, experimental investigation of soil behavior under dynamic loads, soil improvement, seismic geotechnical and embankment dams.

Reza Noorzad was born in Nour, Mazandaran, Iran in 1964. He received both BSc and MSc degrees in Civil Engineering and Geotechnical Engineering from Tehran University, Tehran, Iran in 1990 and 1994, respectively. He also obtained his PhD degree in Geotechnical Engineering from Sharif University of Technology, Tehran, Iran in 2000. He is currently an Associate Professor at the Department of Civil Engineering at Babol Noshirvani University of Technology. From 2004 to 2007, he was the Head of Central Library and Documentation Centre at Mazandaran University. His research interests include soil improvement, reinforced soil, earth dams, marine geotechnics, and geotechnical earthquake engineering.

Bahram Ta´negonbadi was born in Gonbade Kavoos, Golestan, Iran in 1989. He received his BSc degree in Civil Engineering from Ferdowsi University of Mashhad in 2011, and MSc degree in Geotechnical engineering from Sharif University of Technology in 2013. He obtained his PhD degree in Geotechnical Engineering from Babol Noshirvani University of Technology, Bbaol, Iran in 2018. His main research interests are soil stabilization, soil improvement, underground spaces (tunnels) under dynamic loadings, soil-structure interaction, earth dams, and geotechnical earthquake engineering.