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Review Article

State-of-the-Art Review: Fiber-Reinforced Soil as a Proactive Approach for Liquefaction Mitigation and Risk Management

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Soil liquefaction is a phenomenon that occurs in which the behavior of soils changes from solid to viscous liquid due to the effect of earthquake intensity or other sudden loadings. The earthquake results in excess pore water pressure, which leads to saturated loose soil with weaker characteristics and potentially causes large ground deformation and lateral spreading. Soil liquefaction is a dangerous event that can lead to catastrophic outcomes for humans and infrastructures, especially in countries prone to earthquake shaking, where soil liquefaction is considered one of the most prevalent types of ground failure. Hence, precautions to reduce and/or prevent soil liquefaction are essential and required. One of the countermeasures to avoid soil liquefaction is the introduction of fibers in the soil since fibers can act as reinforcement by enhancing the soil's strength and resistance to liquefaction. The process of including fibers into the soil is known as soil stabilization and is considered one of the ground improvement techniques. Therefore, this paper aims to summarize and review the consequences of adding fiber as a reinforcement technique to overcome the issue of soil liquefaction.

1. Introduction

Liquefaction of soil is a serious phenomenon that carries tremendous risks to human lives as well as properties during earthquakes, such as landslides, ground failure, and damage to infrastructure [1–4]. There are diverse types of ground failure caused by liquefaction, including failure of retaining walls as a result of the increase in lateral loads causing them to slide or tilt, lateral spreads as a result of lateral movements, ground settlement, reduction in bearing capacity leading to foundation failure, a buoyant rise of buried structures, and ground oscillation with repetitive displacement. The solution to constructing structures on liquefiable foundations can be either swapping the project location/ structure type or enhancing the foundation situation, but the latter solution is feasible and logical to make [5]. This event mainly takes place in saturated cohesionless soil, which causes the soil to lose its strength and stiffness as well as its ability to withstand the weight of building above it due to an increase in pore water pressure during strong and large amplitude seismic waves resulting in deformation of the soil and thus a reduction in its effective stress as a consequence of dynamic loading [6]. The three types of liquefaction are static, dynamic, and blast, but static, which is caused by rainfall, and dynamic, which is caused by earthquake shaking, are the most common types of liquefaction, followed by blasting, which is considered to be the least likely to happen [7, 8]. The characteristics of soils, such as shear strength and stiffness, are related to the situation of the environment and the type of structure above the soil as well as external factors such as earthquakes [9]. The most susceptible soil type to both static and dynamic liquefaction is fine silty sand due to its engineering properties since the fine or powder content induces static liquefaction compared to clean sand [10–12]. The attention on liquefaction and its hazards were not focused until the occurrence of the Niigata and Alaska earthquakes in 1964 [13], since these disastrous incidents advanced the study and research about the mechanism of soil liquefaction, leading to progress in ground improvement approaches [14–17]. Generally, multiple factors that affect the possibility of liquefaction have been analyzed, including relative density, earthquake magnitude, fine content, saturation degree, vertical stress, and ground motion characteristics [17–19]. Some studies were conducted to evaluate the settlements created by earthquakes and the dissipation of pore water pressure due to liquefaction [20–22]. In addition to that, numerous researchers examined the liquefaction resistance of cohesionless soils in different structures, including embankments, dams, and slopes [23–25]. Currently, there are many methods to eliminate the liquefaction of soil, such as draining, densification, and reinforcement of soil [26]. Nonetheless, soil reinforcement has been the best method to adopt since draining and densification are usually affordable and fruitless [27–29]. One of the ground improvement methods and liquefaction prevention approaches is the inclusion of fibers, for example, glass, polyethylene, steel, and polypropylene, as reinforcement techniques. One of the advanced approaches for mitigating the risk of liquefaction is the utilization of nature-based solutions. These solutions include coconut coir, jute, and sisal fibers which can be an adequate replacement for synthetic fibers for sustainability and cost-effectiveness advantages. Another example of nature-based solutions is the use of vegetation to reinforce soil since vegetation can be used in combination with fiber-reinforced soils to stabilize soil slopes and prevent erosion. Another advanced approach for mitigating liquefaction is the use of nature-inspired solutions which refer to engineering or design approaches that inspired by natural systems and processes. One example of an NIS in FRS is the use of biomimetic geotextiles. These geotextiles are designed to mimic the properties of natural materials such as spider silk, which is known for its strength and flexibility. By using a biomimetic approach, geotextiles can be designed to provide similar or even superior reinforcement properties to traditional geotextiles while also being more environmentally friendly. However, polypropylene is considered to be the most used fiber for soil reinforcement [30–32]. Accordingly, the current state of the art is missing a detailed paper regarding the liquefaction potential of soil and the fiber effect. Therefore, this paper provides a detailed, comprehensive review study on the impact of utilizing different types of fibers as reinforcement techniques on the liquefaction potential of soil. A part of the paper, a review of the available studies concerning the inclusion of natural and synthetic fibers on soil behavior in terms of liquefaction occurrence, was performed. Besides, it discusses and compares the effect of using distinct types of fibers as reinforcement techniques on the soil liquefaction potential.

2. Soil Liquefaction

2.1. Mechanism of Soil Liquefaction. Indeed, soil liquefaction is a phenomenon that usually happens in loose saturated soil with a low potential of existence in viscous rocky clay soil. On the other side, a study on the Wenchuan earthquake showed that gravelly soils are capable of exhibiting liquefaction under particular circumstances [33]. The process of soil liquefaction starts with the compression of the densely packed and sheared sand particles, followed by expansion during the sliding of the sand particles over each other. Saturated sand consists of two porous layers of soil particles and pore water. The densely sheared saturated sand particles hinder the pore water drainage due to the dynamic effect causing a rise in volume, shear strength, and effective stress accompanied by a decline in pore water pressure. The initiation of excess pore water pressure as well as weakening of the soil and the increment of deformation are related to the behavior of dense soil under small cyclic shear strain within undrained pore water circumstances [6, 34]. As the shear strain increases, the volume increases as well, resulting in a decrease in excess pore water pressure and hence an increase in shear resistance of the soil. Limited liquefaction occurs when a great amount of deformation is impeded after cyclic loadings stop due to the accumulated undrained shear strength resulting in strain hardening [6, 35]. On the other hand, cyclic mobility can be defined as the gradual weakening of dense saturated sand under static load within limited undrained cyclic shear strain [36]. Soil liquefaction is a different event from cyclic mobility since liquefaction exerts a negligible rise in shear resistance despite the value of deformation [37]. The soil subjected to cyclic mobility shows softening first, followed by stiffness in case the monotonic loading was applied in the absence of drainage due to a rise in volume and decrease in pore water pressure. Furthermore, the soil subjected to cyclic loading builds up deformation and produces a low magnitude of static shear pressure in comparison to residual shear resistance. However, the term "cyclic liquefaction" was introduced in 1994, which describes the existence of deformation as the static shear pressure surpasses the shear resistance of the soil [38]. The condition at which the initial static shear pressure of expansible soil is not appreciable is called the zero effective stress state [38, 39]. In general, soil liquefaction can be categorized into flow failure, circulating fluidity, and sand boils [40]. Sand liquefaction is the phenomenon where the ratio of pore water pressure reaches one while the sand strength approaches zero and the sand is in the liquid state [41, 42]. Lastly, the liquefaction of saturated sand during an earthquake must meet two fundamental requirements, which are the existence of adequate vibration intensity capable of ruining the structure of the soil and the development of the progressive rise of excess pore water pressure as the number of stress cycles increases until the value of excess pore water pressure causes the shear strength of the sand to diminish entirely or partially [43].

2.2. Evaluation of Soil Liquefaction. Different approaches were suggested to detect the factors responsible for the evaluation of liquefaction resistance of soil, including stress-based [44], strain-based [45], and energy-based [46, 47]. The most widely used approach is based on the shear stress and several cycles as the criteria of assessment regardless of the predicament of measuring effective uniform shear stress or shear strain during tests [44]. Another approach is based on the dissipated energy, initial effective stress, and high pore water pressure which has been utilized by numerous

FIGURE 1: Coir fiber (a) and banana stem fiber (b) (reproduced from [56]).

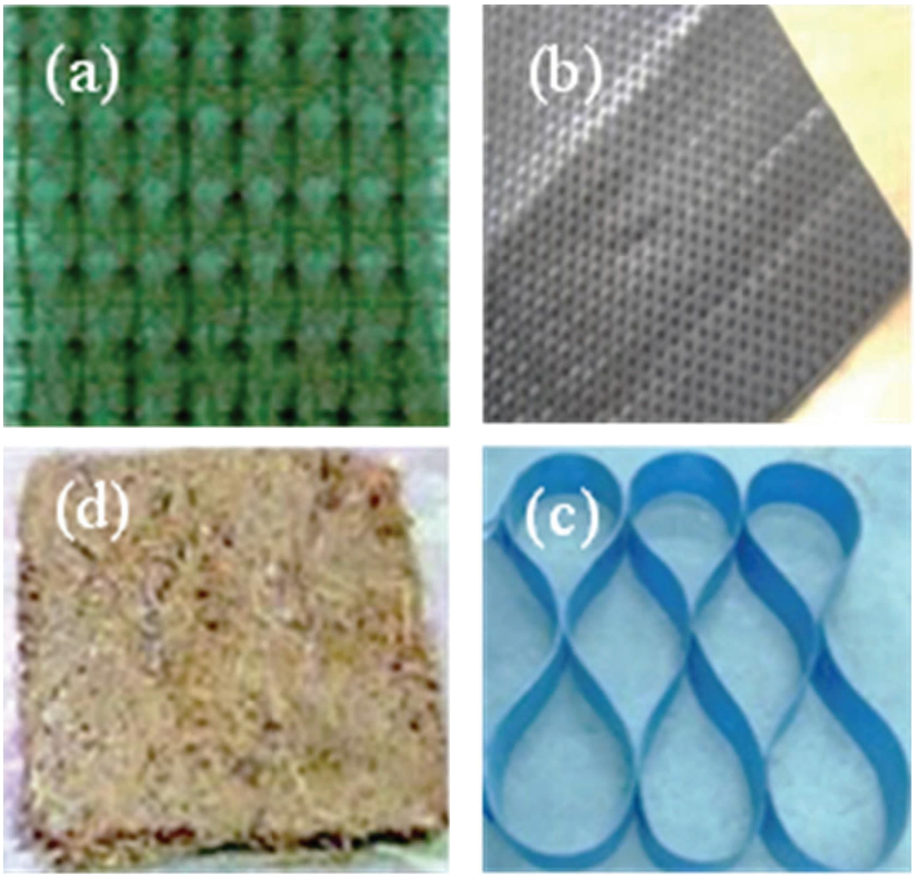


FIGURE 2: Various types of geosynthetics used in the tensile test experiment. PYRAMAT (a), TS570 geotextile (b), 8FG MAT (c), and OPEFB biocoat (d) (reproduced from [57]).

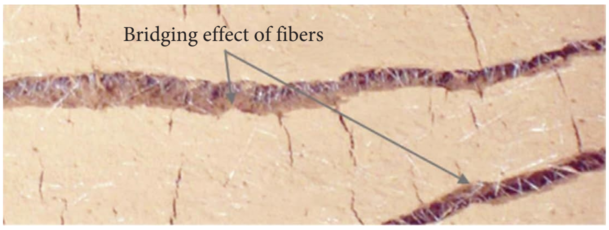


FIGURE 3: Bridging effect of fibers across the crack opening (reproduced from [58]).

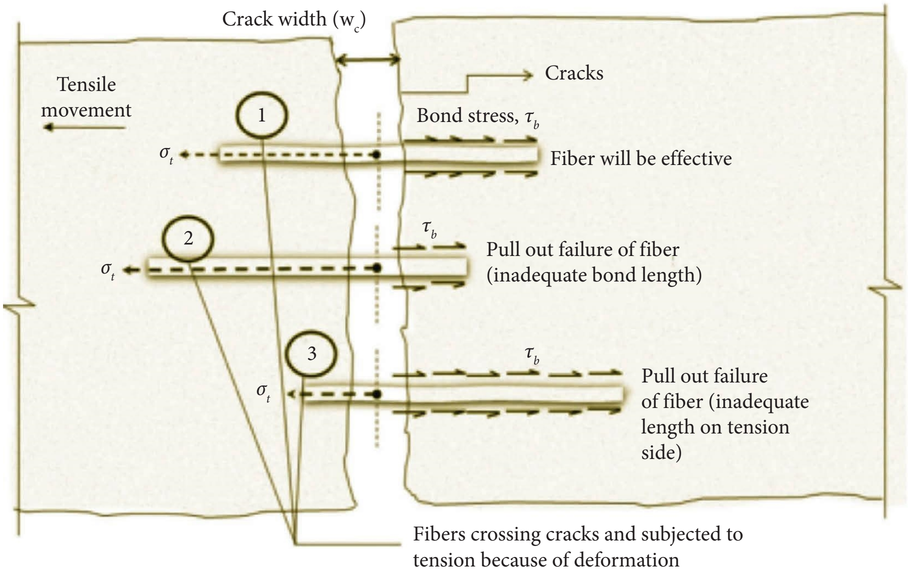


Figure 4: Schematic diagram of fibers undergoing tension (reproduced from [59]).

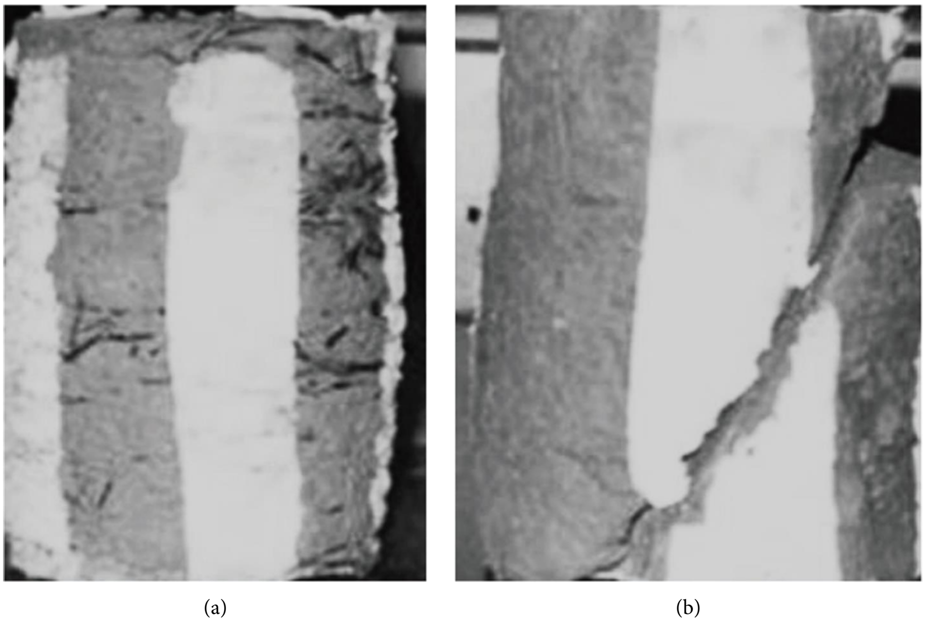

(a) (b)

Figure 5: Sample deformation pattern for (a) unreinforced clay soil specimens and (b) clay soil reinforced with 0.25% PP (reproduced from [60]).

researchers due to its simplicity in evaluating the liquefaction resistance of soil [46, 48, 49]. The energy-based approach involves using distinct factors to assess soil liquefaction such as the relationship between the generation of pore water pressure and energy release [48], the energy attenuation equation [49], the energy principles [50], and the shear energy as a replacement to shear strain and a number of cycles [51]. In general, the most common tests for sand liquefaction are the direct shear test and triaxial test despite the fact that the sample volume and strain range in the traditional direct shear test apparatus and triaxial test apparatus is little which yields some drawbacks during the assessment of sand liquefaction. The ring shear test apparatus is an adequate device for evaluating sand liquefaction due to its advantages such as big strain range and sustained shear surface [52–54].

3. Fiber as Reinforcement Technique in Soil

Fiber is a material that possesses flexibility, a large length to thickness ratio, and fineness properties. Usually, fibers are randomly mixed with soil creating fiber-reinforced soil (FRS)

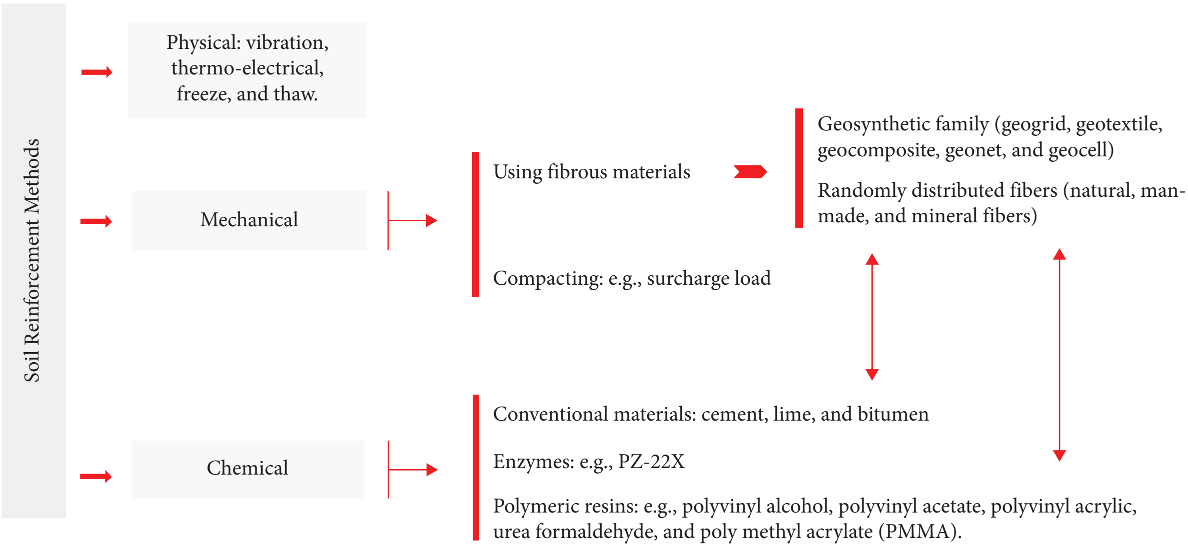


Figure 6: Different procedures of soil reinforcement (reproduced from [67]).

with the main purpose of enhancing the strength characteristics and other qualities of the soil [55]. Reinforcement of soil can be defined as the procedure of mixing materials with the soil in order to enhance the soil's properties. Generally, fiber reinforcement can be divided into natural, synthetic, and waste fibers depending on the source of the material. Natural fibers such as coconut (coir) and palm fibers have advantages such as high strength, low cost, and good impact on the environment as illustrated in Figure 1.

Synthetic fibers such as polypropylene (PP), polyester, and glass fibers are manufactured to meet the desired requirements which enable the control and modification of soil geometry to improve the characteristics of fibers, especially under the variable environmental factors as presented in Figure 2.

Waste fibers such as old or used tires and waste plastic fibers are incorporated as soil reinforcement which can eliminate the environmental issues related to the disposal of these materials. Fibers can be added to soils either as oriented or random where the oriented approach focuses on systematically arranging the fibers layer by layer in the same orientation and the random approach focuses on mixing the fibers with soil discretely which provides strength isotropy and minimize the potential of forming weak planes as demonstrated in Figure 3. The mechanism of fiber going under tension is shown in Figure 4.

As can be observed in Figure 5, the advantages of using these fibers are the availability of these materials [61–63], the development of the strength characteristic [64, 65], and the hindrance of the tensile crack propagation [66, 67].

The result of the inclusion of fibers in the soil is the rise in the peak shear strength and minimization of the postpeak reduction in shear resistance as well as a rise in the stiffness and cohesion of the mixture. In addition to that, a certain fiber content percentage can result in better bonding between the soil particles as well as enhance the structure of soil and reduce displacement. Figure 6 shows the soil reinforcement methods.

4. A Summary of Various Types of Fiber Material Utilized in Soil

Indeed, this section is intended to illustrate the various types of fibers that were previously used to reinforce soil materials as well as to briefly highlight the advantages and influence of each type.

4.1. Natural Fibers. The possibility of utilizing natural fibers in soil reinforcement has been the interest of many studies recently due to the need for eco-friendly materials in the field of ground improvement. However, the incorporation of natural fiber has been implemented for some time in some developing countries in cement mixtures and block applications due to the cost-effectiveness and availability [68–70]. In fact, there are some factors affecting the quality of natural fiber including the age of the plant, the method of isolating the fiber, and the place in the plant where fiber is brought from [71]. There are different types of natural fibers and each type will be concisely discussed.

4.1.1. Coconut (Coir) Fiber. It is the outer surface of a matured coconut (coconut husk) with a length ranging between 50 and 350 mm. One of the substances composing coir fiber is lignin which is responsible for the slow degradation and long infield life between 4 and 10 years in comparison to other natural fiber types [67]. Coir fiber degrades based on the climate situations and the nature of implementing soil where the coir fiber sustained 80% of its tensile strength beyond 6 months of implementing the fiber in clay. Coir fiber is stronger and more flexible in nature due to the high friction coefficient compared to synthetic fibers whereas some coir fibers provided 47.50% development in resilient modulus compared to synthetic fibers which exhibited only 40% [72]. In addition, coir fiber distributed randomly exhibited satisfying performance in minimizing the possibility of swelling of soil [73, 74].

Table 1: Effects of using natural fiber in soil on its liquefaction potential.

Authors	Test apparatus	Type of reinforced soil tested	Remarks
Lawton et al. 1993 [101]	California bearing ratio (CBR), triaxial, and permeability tests	A nonplastic, residual silty micaceous sand and Ottawa sand mixed with multioriented geosynthetic	The usage of multioriented geosynthetics rises the stiffness of the soil. Furthermore, a 584% increase was seen in the stress-strain modulus and a 106% increase was seen in deviator stress at failure. Multioriented and fiber geosynthetics reduce the penetration resistance at small values whereas fiber exhibited better resistance at larger penetration values. Finally, fiber reinforcement was seen to provide a better effect on the soil compared to multioriented at the same amount. The optimum fiber content was 3% by volume
Rao et al. 2005 [100]	Triaxial compression test	Yamuna sand reinforced with coir fiber and coir geotextiles	The inclusion of coir fiber rises the shear strength and increases the deviator stress at failure. Randomly distributed coir fiber displayed far superior strength in comparison to layered coir fiber. The usage of reinforcement showed influence in the reduction of volumetric expansion. The reinforced and unreinforced sand exhibited the same increasing effect on the initial tangent and secant modulus with the increase in confining pressure. The optimum coir fiber content was 1% by weight
Damarashetty et al. 2006 [102]	Triaxial compression test	Sand mixed with coir fiber	The integration of coir fiber as a reinforcement element in the sand was seen to increase the effective friction angle up to critical confining pressure of 49 kPa. Past the critical pressure, the effective cohesion. Coir fiber can be utilized in the ground improvement of soil. The optimum fiber content was 1%
Sivakumar Babu and Vasudevan 2008 [62]	Triaxial shear test	Clay mixed with coir fiber	The presence of coir fiber (1%–2%) in the soil leads to stiffness and strength increase. Additionally, the usage of fiber enhances the stress-strain relationship. The maximum increase in stress can be achieved with the fiber length between 15 and 25 mm. The use of fiber in the soil causes a rise in the stiffness of the mixture in terms of minimizing the immediate settlement. The optimum fiber content found to be 2%–2.5% (by weight of soil)

Table 1: Continued.

Authors	Test apparatus	Type of reinforced soil tested	Remarks
Kafodya and Okonta 2019 [103]	Undrained cyclic and postcyclic shear tests	The soil used is a mixture of clay-silt, sand, and gravel with sisal fiber	The increment of shear modulus was related to the fiber content up to 0.5% where beyond that the shear modulus starts decreasing due to the drop in stiffness of the soil mixture caused by the presence of voids. As the confining pressure increased, the shear modulus increased. The usage of fiber and the increment in confining pressure improved the damping ratio due to the improvement in the resistance of soil mixture to deformation. The liquefaction resistance was seen to be high in unreinforced and reinforced soils due to the presence of fine particles while fiber limited the generation of pore water pressure. The optimum fiber content was 0.5%
Ertuğrul and Canoğulları 2022 [104]	Regression analysis using the results of the other related studies	Different soils mixed with different natural and synthetic fibers	Regression analysis was performed using previous studies in the field to examine the effect of adding natural or synthetic fibers on the liquefaction of soil by means of relative density and fiber content. The results of the proposed formula obtained using regression analysis matched the results of previous studies with a coefficient of determination of 0.90 in which the increase in fiber percentage increased the number of cycles to reach liquefaction. The optimum fiber content was 1% which represented the best improvement against liquefaction

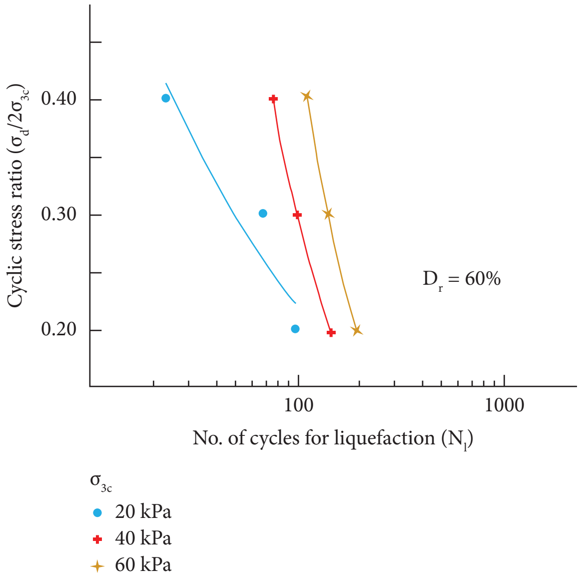


FIGURE 7: Variation of cyclic stress ratio with the number of stress cycles for liquefaction (reproduced from [105]).

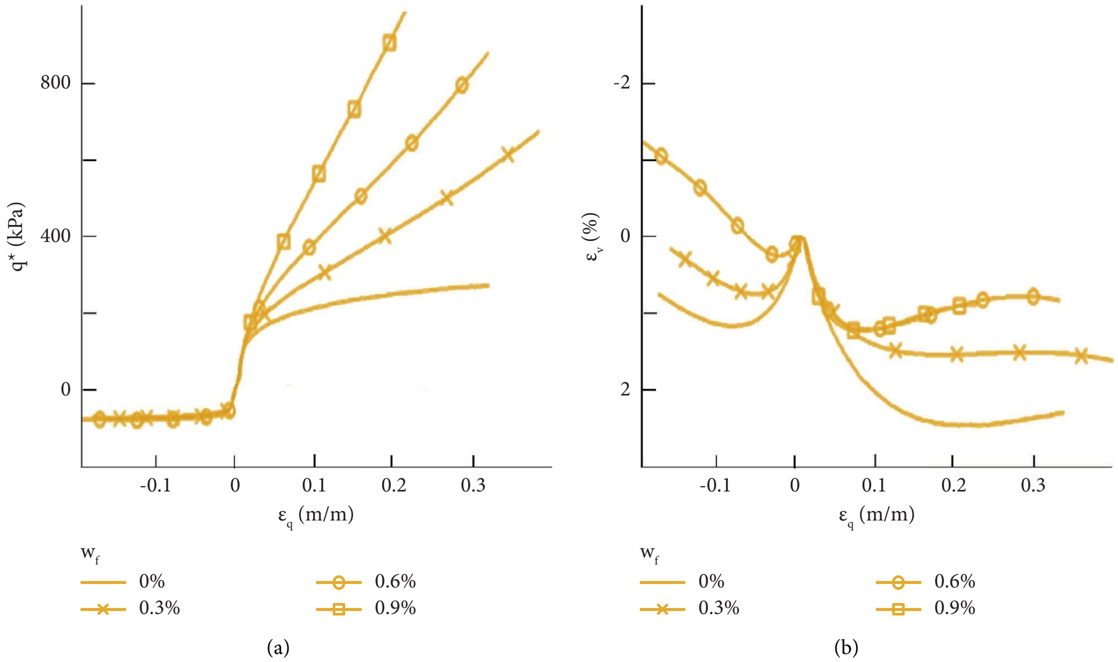
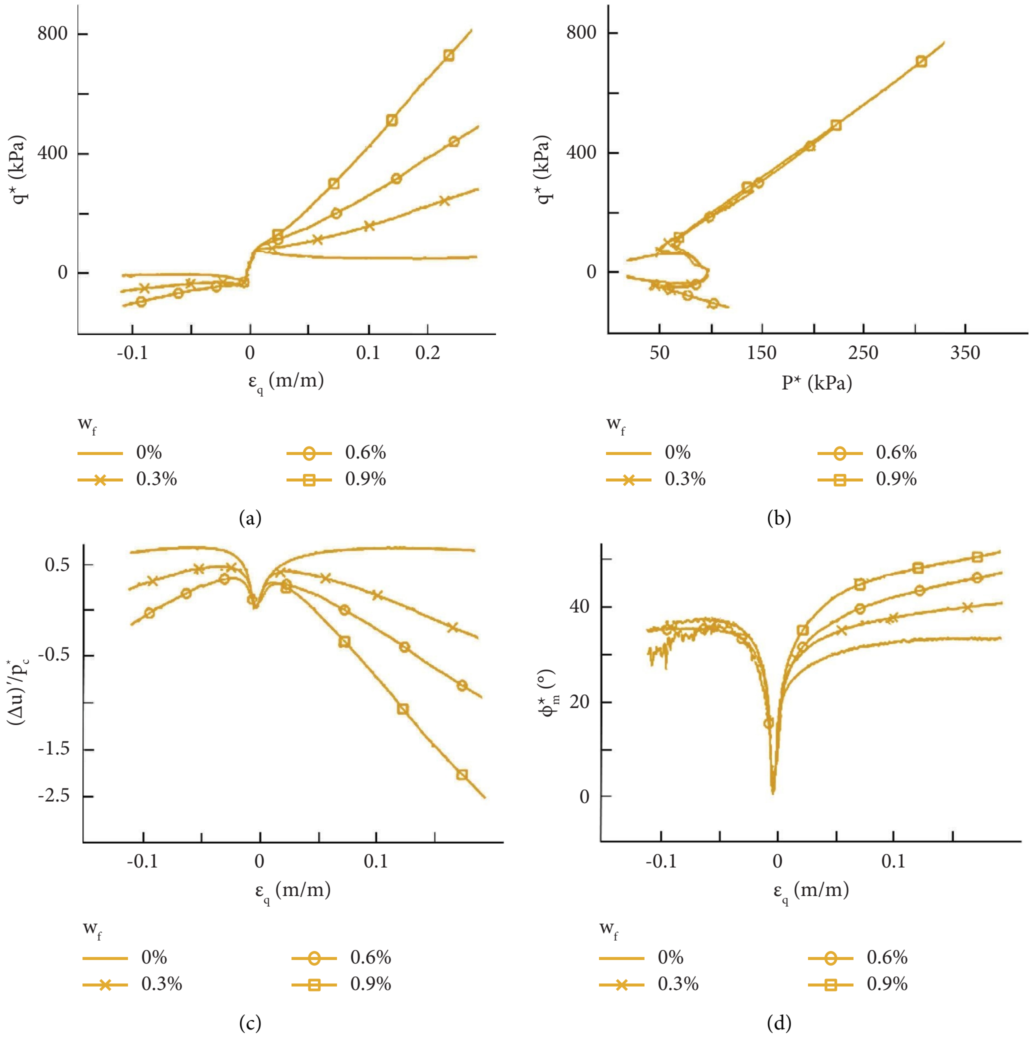


FIGURE 8: Deviator stress-shear strain and volumetric behavior for drained compression and extension triaxial tests (reproduced from [106]).

4.1.2. Sisal Fiber. It is the product of the leaves of the plants that generally grow in Indonesia, Brazil, and East African countries with length ranges between 50 and 250 cm and width ranges between 6 and 10 cm [75]. The inclusion of sisal fiber or coir fiber with 4% reflected a significant effect on the ductility and a slight increment in the compressive strength [68]. Moreover, the fiber percentage and fiber length were noted to affect the dry density in an inversely proportional manner where any increase in these two parameters results in a decrease in the dry density of the soil [76]. Lastly, as the percentage of sisal fiber increases, the shear strength increases up to 0.75% fiber content where any further increase leads to a reduction in the shear strength.

4.1.3. Palm Fiber. The material obtained from degraded palm trees exhibits low tensile strength, brittleness, low modulus of elasticity, and high-water absorption [77].



(a) (b) (c) (d)

Figure 9: Triaxial undrained compression and extension tests; 100 kPa initial consolidation pressure (reproduced from [106]).

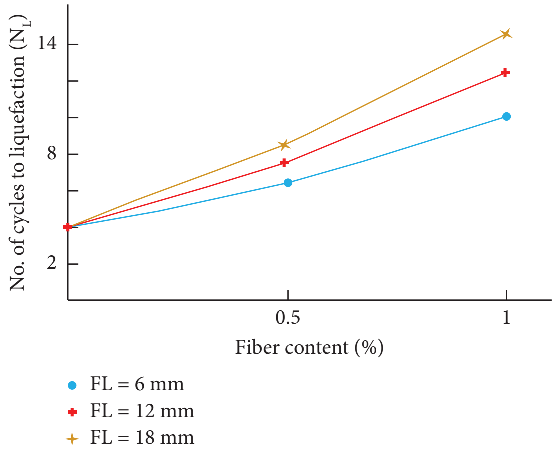


Figure 10: Number of cycles causing liquefaction versus fiber content at various fiber lengths (Dr = 40% and CP = 100 kPa) (reproduced from [5]).

However, the currently produced palm fiber possesses unique characteristics including durability, cost-effectiveness, tensile capacity, availability, and relative strength to combat deterioration [78]. The increment in fiber percentage between 0% and 1% while the fiber length is constant results in an increase in the maximum and residual

Table 2: Effect of fiber length on Babolsar sand (Dr = 40% and FC = 1%) [5].

Cyclic stress ratio	Sand only	FL = 6 mm		FL = 12 mm		FL = 18 mm	
	N_L	N_L	Improvement (%)	N_L	Improvement (%)	N_L	Improvement (%)
1	2.5	6	140	7	180	9.5	280
0.5	4	10	150	12.5	213	14.5	263
0.25	25	58	132	67	168	80	220

strength as well as a reduction in the difference between the maximum and residual strength [66]. The integration of palm fiber in soil considerably improved the deviator stress at failure and shear strength parameters [79].

4.1.4. Jute. The material obtained from the bark of jute plants with a length up to 2.5 m generally grows in China, India, Bangladesh, and Thailand. Typically, jute is considered eco-friendly material with different applications such as stabilization of soil, drainage, and filtration [67]. The fiber utilized in the stabilization of soil in pavement applications is commercially named GEOJUTE which is woven from jute fibers. Lastly, the maximum dry density is minimized with the inclusion of jute fiber whereas optimum moisture content increases.

4.2. Synthetic Fiber. It is manufactured fiber with a longer life than natural fiber. The length and form of fiber are completely controlled by man whether making it into staple or cut. Unlike natural fiber, synthetic fiber such as polypropylene (PP), polyester (PET), and polyethylene (PE) are harmful to the environment. Synthetic fiber has been utilized in the field of soil reinforcement due to its high tensile strength and good corrosion resistance [80, 81]. There are different types of synthetic fibers and each type will be briefly discussed.

4.2.1. Polypropylene (PP) Fiber. It is the most prevailing man-made fiber used in the reinforcement of soil. [30–32]. PP fiber is implemented for numerous advantages, including minimizing the shrinkage characteristics, combating biological and chemical degradation, and improving the strength characteristics [82–84]. In addition to that, PP fiber proved its ability to increase the unconfined compressive strength, decrease swell pressure, and volumetric shrinkage strain for expansive clays [84, 85]. It was seen that soils reinforced with PP fiber provided hardness during the load-settlement response test compared to unreinforced soils, which displayed almost perfectly plastic behavior making this fiber applicable for soil reinforcement in embankments and shallow foundations [86]. Lastly, the conclusion of performing conventional triaxial compression and tension test was that including fibers significantly increased strength in compression but showed a negligible effect in tension [87].

4.2.2. Polyester (PET). The fiber content is the crucial factor in enhancing the ultimate and peak strength of the soil [88]. Moreover, the fiber content and fiber length influenced the unconfined compressive strength, ultimate bearing capacity, and settlement of highly compressible clay, where any increment in the fiber content and fiber length led to an increment in unconfined compressive strength and ultimate bearing capacity as well as led to a reduction in settlement of the soil [89, 90]. Short PET fiber was proved its ability to enhance the stability of levees against seepage and flood since it possesses strong piping resistance [91].

4.2.3. Polyethylene (PE). PE fiber is fundamentally used in geotechnical engineering due to its environmentally friendly properties. The usage of high-density PE fiber led to an increment in the fracture energy, tensile strength, toughness, and strain capacity of the soil [92, 93]. Another application of high-density PE fiber is the implementation in pavement engineering as a subgrade material in order to decrease the thickness of the base course [92].

4.2.4. Glass Fiber. The integration of glass fiber in soil showed a notable effect on peak strength [94, 95]. A comparative study regarding the influence of PP, PET, and glass fiber on the mechanical behavior of reinforced soils was conducted where it was found that using PP fiber considerably enhanced the brittleness and decreased the deviator stress at failure, while PET and glass fibers improved the deviator stress at failure and decreased the brittleness [96]. The addition of glass fiber to the soil exhibited a significant effect on the unconfined compressive strength, where the addition of 1% of glass fiber to 4% cemented sand resulted in 1.5 times increase in comparison to unreinforced sand [97].

5. Influence of Fibers on the Liquefaction Potential of Soils

This section is devoted to highlighting and reviewing the remarkable studies on the utilization of fibers as reinforcement techniques to mitigate the potential of liquefaction in soil. Generally, Krishnaswamy and Isaac [26, 98] performed stress-controlled triaxial tests to examine the influence of adding coir fiber and geotextile fibers on the liquefaction resistance of the sand. It was found that the addition of fiber, stress ratio, effective confining pressure, and interface friction all improved the liquefaction resistance of the sand [26, 98]. Another study conducted by Maheshwari et al. [99] investigated the effect of including different types of fiber on the liquefaction resistance of the sand. It was found that coir fiber exhibited the best performance among fibers where 0.75% coir fiber content at 0.1 g acceleration increased the liquefaction resistance by 91%. Furthermore, as the fiber content increases, the

Table 3: Impact of synthetic fiber on soil liquefaction.

Authors	Test apparatus	Type of reinforced soil tested	Remarks
Maher and Gray 1990 [107]	Triaxial compression tests	Muskegon dune sand and mortar sand mixed with rubber, reed (natural), and glass (synthetic) fibers	The integration of fiber heavily influenced the stiffness and ultimate strength of the soil due to parameters including aspect ratio and weight fraction of fiber as well as gradation and particle geometry. The addition of fiber, as well as fiber modulus, is linearly proportional to the increase in shear strength. The optimum glass fiber content was 3% (by weight) with lowest fiber aspect ratio (L/d) of 60
Krishnaswamy and Isaac 1994 [26]	Stress-controlled cyclic triaxial test	Woven (polypropylene), nonwoven geotextile, and coir fibers with sand	Coir fiber provided the best performance in terms of liquefaction resistance due to the high soil-fiber interface followed by nonwoven geotextiles due to high stiffness and lastly woven geotextiles. Hence, the liquefaction resistance increases as the stiffness, stress ratio, and interface friction increase. Moreover, the effect of fiber on liquefaction resistance increases as the spacing of reinforcement and relative density decrease. No percentage of fiber content was presented in the study
Ranjan et al. 1994 [108]	Triaxial compression test	Sand with plastic fiber	The presence of fibers in the sand increases the peak shear strength and decreases the loss of postpeak stress. Moreover, the increase in shear strength is directly attributed to the increase in fiber content by up to 2%. The shear strength rises with the increase in fiber aspect ratio while critical confining stress is reduced. The optimum fiber content was 2% (by weight) with fiber aspect ratio ranging between 60 and 90
Krishnaswamy and Thomas Isaac 1995 [98]	Cyclic triaxial test	Woven (polypropylene), nonwoven geotextile, and coir fibers with sand	Woven, nonwoven, and natural coir fibers were added in one and two layers to the soil. The soil-fiber interface, bending stiffness, and compressibility of fiber have a significant impact on the shear mobilization. Moreover, the stiffness of fiber is proportional to the shear mobilization where any increase in the stiffness increases shear mobilization. On the other hand, the compressibility of fiber is inversely proportional to the shear mobilization where any increase in compressibility results in a decrease in the shear mobilization. The best result was seen in the case of coir fiber with one layer where it produced the highest angle of interface friction and stiffness

Table 3: Continued.

Authors	Test apparatus	Type of reinforced soil tested	Remarks
Vercueil et al. 1997 [27]	Cyclic triaxial test	Hostun RF sand reinforced with nonwoven geotextiles (polyester)	When the stress ratio is lower than the cyclic resistance, the liquefaction resistance rises due to the friction between soil and fiber. In case, the stress ratio is higher than cyclic resistance, the liquefaction resistance increases due to the deformable nature of the fiber. During testing, the sand is subjected to repetitive expansion cycles but the fiber causes a delay in the liquefaction by means of minimizing the interstitial pressure in the sand. No specific optimum fiber content was presented in the study
Boominathan and Hari 2002 [105]	Stress-controlled cyclic triaxial test	Fly ash with fiber and mesh (nonwoven polypropylene geogrid sheets) reinforcement	The incorporation of geosynthetic fiber and mesh reinforcement is inversely proportional to the confining stress and relative density where any decrease in confining stress and relative stress results in a rise in liquefaction resistance. However, mesh reinforcement showed better performance compared to fiber reinforcement because mesh reinforcement produces better interlocking and easier pore water pressure dissipation. The optimal fiber/mesh content to increase liquefaction resistance is approximately 2%
Altun et al. 2008 [109]	Cyclic torsional shear test	Toyoura sand reinforced with (woven, nonwoven) geosynthetics	The addition of fibers to sand resulted in an increase in the liquefaction resistance up to 266% and 258% for one and four layers of woven and nonwoven geotextiles respectively. Furthermore, the type (woven and nonwoven) and arrangement (from one to four layers) of fiber play an important role in the liquefaction resistance of the soil. Woven and nonwoven geotextiles enhanced the liquefaction resistance of reinforced soil because the sand layers are isolated by geotextiles. Soil mixed with nonwoven geotextiles exhibited superior performance in terms of liquefaction resistance due to its dense structure and low elastic modulus in comparison to woven geotextiles. The best performance was exhibited by four layered nonwoven geotextiles at stress ratio of 0.125

Table 3: Continued.

Authors	Test apparatus	Type of reinforced soil tested	Remarks
Diambra et al. 2010 [87]	Conventional triaxial compression and extension test	Hostun RF sand reinforced with short polypropylene fibers	The modeling method is quietly useful for enabling different fiber orientation functions. The fiber heavily influences the strength in compression but has negligible influence on strength in tension due to orientation in regard to tensile strains. The optimum fiber content was 0.9% (by weight)
Ibraim et al. 2010 [106]	Conventional drained and undrained triaxial compression and extension test	Hostun RF sand with Loksand flexible polypropylene crimped fibers	During the drained test, the increase of strength due to the addition of fibers is directly dependent on the content and direction of the arrangement. The volume of the mixture is highly affected by fibers for compression and tension loading since fibers fill the voids in the sand despite the fact that the stress-strain relationship is slightly affected. During undrained, the increase of strength due to the addition of fibers for both compression and tension is clearly noticeable as well as transforming softening of strain into hardening. Finally, the inclusion of fiber resulted in minimization or elimination of static liquefaction for both compression and extension regardless of the fact that liquefaction in extension requires a higher number of fibers. The optimum fiber content was 0.9% (by weight)
Noorzad and Omidvar 2010 [110]	Fully coupled nonlinear effective stress dynamic analysis	Nonwoven geotextile layers with clay	The incorporation of fiber into clay limited the crest settlement, maximum shear strains as well as horizontal and vertical displacement of the embankment. In addition to that, fibers intensified the maximum horizontal crest acceleration. No specific optimum fiber content was presented in the study. However, the average efficiency of the used nonwoven geotextile was 0.8. The highest reduction of horizontal and vertical displacements for the dam heights of 15, 25, and 40 m was recorded with 1.5 m geotextile spacing

Table 3: Continued.

Authors	Test apparatus	Type of reinforced soil tested	Remarks
Liu et al. 2011 [111]	Undrained ring shear test	Silica sand with polypropylene fiber	The addition of polypropylene fiber showed little to no significant effect on the loose reinforced sand regardless the reinforced specimen maintained structural stability whereas the unreinforced one completely failed. Hence, fibers possess the ability to reduce or eliminate the lateral spreading of sand. On the other hand, the addition of fiber showed a noticeable effect on moderately dense and dense reinforced specimens in terms of displaying fluctuations after shear failure, unlike unreinforced samples. In addition to that, moderately dense and dense reinforced specimens as well as dense unreinforced specimens maintained structural stability in comparison to the moderately dense unreinforced specimen which partly failed. Lastly, fiber reinforcement provided partial decrease or entire prevention of the lateral spreading caused by static liquefaction. The optimum fiber content was 0.8% (by weight)
Maheshwari et al. 2012 [99]	Vibration (shake) table	Solani sand reinforced with a geogrid sheet, geosynthetic fiber, and natural coir fiber	The inclusion of coir fiber reflected the best result in terms of liquefaction resistance compared to other reinforcement types. Coir fiber at 0.75% and 0.1 g acceleration provided improvement of liquefaction resistance up to 91% while synthetic fiber at the same fiber percentage and acceleration magnitude provided 88% improvement and geogrid sheets (five layers) at the same acceleration magnitude provided 31% improvement. The addition of fibers is inversely proportional to the acceleration magnitude whereas any reduction in acceleration magnitude (from 0.4 g to 0.1 g) leads to an increase in liquefaction resistance. Lastly, the reinforced sand exhibited a good effect by means of minimizing the settlement. The optimum fiber content was 0.75% (by weight) for coir fiber and geogrid sheets (five layers)

Table 3: Continued.

Authors	Test apparatus	Type of reinforced soil tested	Remarks
Wang and Brennan 2013 [112]	C67-2 geotechnical centrifuge modeling	HST95 congleton sand with crimped polypropylene fiber	The presence of fiber in soil enhanced the liquefaction resistance by means of increasing the shear stress cycles to reach the maximum excess pore water pressure. No specific fiber content was presented in the study
Noorzad and Amini 2014 [5]	Stress-controlled cyclic triaxial test under undrained conditions	Babolsar sand with randomly distributed monofilament polypropylene	Fiber content and length showed a crucial positive effect on the required cycles number to reach liquefaction. 1% fiber content resulted in the highest liquefaction resistance of 280%. Shear modulus improves with the increase of fiber content. Lastly, fibers can be useful in reducing or eliminating the lateral movement of soil due to liquefaction. The optimum fiber content was 1% (by weight)
Wang and Brennan 2015 [113]	Two centrifuge tests	HST95 congleton sand redhill 100 sand with flexible crimped polypropylene fiber	The inclusion of fiber in the backfill significantly limited the lateral displacement of the quay wall and backfill settlement. The usage of fiber as reinforcement in soil prevented quay wall movement caused by excess pore water pressure. The optimum fiber content was 0.6% (by weight)
Huang and Wang 2016 [114]	Dynamic triaxial test	Liquefiable silt and silty sand with laponite (synthetic layered silicate nanoparticle)	The integration of laponite in the soil prevents liquefaction by means of soil grain cementation, and pore fluid solidification and limits the initiation of pore pressure. The transition in laponite enhanced the liquefaction resistance. The addition of laponite to the soil slows the formation of pore pressure and reduces the deformation in comparison to unreinforced specimens. Despite the fact that the increase in laponite content or curing period increased the liquefaction resistance, during the first few cycles, the influence of laponite is higher while the influence of the curing period is higher after a few cycles. The optimum laponite content was 3.5% (by weight)

Table 3: Continued.

Authors	Test apparatus	Type of reinforced soil tested	Remarks
Ye et al. 2017 [115]	Cyclic triaxial compression test under undrained conditions and hollow cylinder torsional shear test	Fujian standard sand with polypropylene fiber	The inclusion of fiber in soil increased the number of cycles to reach liquefaction and hence, increased the liquefaction resistance. The fiber content and fiber length are linearly proportional to the liquefaction resistance where any increase in these parameters increased the liquefaction resistance. The incorporation of fiber in soil minimized the potential of liquefaction in both tests. The optimum fiber content was 0.8% (by weight) and the optimum fiber length was 12 mm
Amini and Noorzad 2018 [116]	Cyclic triaxial test	Babolsar sand with randomly distributed white monofilament polypropylene	The integration of fiber into sand raised the number of cycles to reach liquefaction and hence, the reinforced soil provided higher cumulative dissipation energy needed to initiate liquefaction compared to unreinforced soil. Moreover, the usage of fiber in soil increased the energy absorption capacity and in turn increased the liquefaction resistance. This is attributed to the confining pressure and relative density where the highest increase in energy absorption capacity was recorded at 250% with 1% fiber content and 40% relative density. The fiber content and fiber length are linearly proportional to the energy needed to trigger excess pore water pressure. The optimum fiber content was 1% (by weight) and the optimum fiber length was 18 mm
Karakan et al. 2018 [117]	Stress-controlled cyclic triaxial test under undrained conditions	Loose sands, medium sands, and dense sands monofilament polypropylene fiber	The presence of fiber decreases the possibility of liquefaction. Additionally, the fiber ratio was found to increasingly influence the number of cycles to reach liquefaction. Poorly graded sand is highly affected in terms of liquefaction resistance by the addition of fiber and relative density. Another parameter affecting the soil is fiber length where the increase in fiber length increases the cyclic stress ratio because the soil matrix is linked better with longer fiber. The maximum enhancement in liquefaction resistance was noticed with 1% fiber content, 12 mm fiber length, and 50% relative density

Table 3: Continued.

Authors	Test apparatus	Type of reinforced soil tested	Remarks
Sonmezer 2019 [118]	Strain-controlled cyclic simple shear test	Clean beach sand from the Gallipoli beach with monofilament polypropylene fiber	The combination of fibers in soil notably improved the number of cycles to reach liquefaction and hence, minimized the lateral movement of the soil leading to higher liquefaction resistance. Additionally, the presence of fiber in soil and the increment of fiber percentage, as well as the increment of fiber length all, limited the generation of excess pore water pressure which is attributed to the increment of energy absorption capacity. Moreover, the increment of relative density is linearly proportional to the increment in liquefaction resistance. The influence of fiber percentage on moderately dense sand (50%) was stronger than that on loose sand (30%). Lastly, the increment of fiber percentage showed the most significant effect on sand compared to the increment of fiber length. The optimum fiber content was 1% (by weight) and the optimum fiber length was 19 mm
Ghadr et al. 2020 [119]	A pneumatic controlled cyclic triaxial test under undrained conditions	Two types of sand, sand A F161 (Firoozkuh 161) and sand B F141 (Firoozkuh 141) mixed with thermoplastic polymeric microsynthetic fiber	Reinforced and unreinforced soils experience the transition from initial random loose packing (RLP) to random close packing (RCP) with the increase in silt content. In general, the increment of fiber percentage is accompanied by the increment of average contact number per particle, higher excess pore water pressure dissipation, and enhanced liquefaction resistance. The optimum fiber content was 1.5% (by weight)
Zhang and Russell 2020 [120]	Drained and undrained triaxial compression tests	Sydney sand mixed with crimped polypropylene Loksand fibers	During the drained test, the incorporation of fibers in loose soil exhibited considerable development in the strength of the soil based on the fiber percentage where any increase in fiber percentage produced higher strength. The combination of fibers with soil eliminated the static liquefaction except when the fiber content is low (0.25%) in comparison to unreinforced sand where static liquefaction is presented despite the initial confining pressure. The optimum fiber content for the consolidated drained was 0.5% and the optimum fiber content for the consolidated undrained was 0.75%

acceleration magnitude decreases. Rao et al. [100] observed that the addition of coir fiber to the soil enhanced shear strength and deviator stress at failure, as well as reduced the volumetric expansion. In addition, it was found that the use of randomly distributed coir fiber showed superior strength in comparison to layered coir fiber. Lastly, the reinforced and unreinforced sand increased the initial tangent, secant modulus, and confining pressure. A study performed by Sivakumar Babu and Vasudevan [62] stated that the usage of fiber content between 1% and 2% increased the shear and stiffness of the soil. The integration of coir fiber increased the stress-strain behavior where the maximum increase was achieved with fiber length between 15 and 25 mm. Indeed, a summary of the previous investigations about the effects of utilizing natural fiber in soil on liquefaction potential is arranged chronologically as shown in Table 1.

On the other hand, Vercueil et al. [27] conducted a cyclic triaxial test to investigate the influence of nonwoven geotextiles on Hostun RF sand and found that when the stress ratio is lower than the cyclic resistance, the liquefaction resistance increases due to the friction between the soil and fiber. In case, the stress ratio is greater than the cyclic resistance, the liquefaction resistance increases due to the deformability of the fiber. Another study by Boominathan and Hari [105] found that the inclusion of geosynthetic fiber and mesh reinforcement is inversely proportional to the confining pressure and relative density where any decrease in confining stress and relative stress results in a rise in liquefaction resistance. However, mesh reinforcement showed better performance compared to fiber reinforcement because mesh reinforcement produces better interlocking and easier pore water pressure dissipation as shown in Figure 7. The optimal fiber/mesh content to increase liquefaction resistance is approximately 2%.

Ibraim et al. [106] performed conventionally drained and undrained triaxial compression and extension test and found that during the drained test, the increase of strength due to the addition of fibers is directly dependent on the content and direction of the arrangement, as seen in Figures 8 and 9.

In addition to that, the volume of the mixture is highly affected by fibers for compression and tension loading since fibers fill the voids in the sand despite the fact that the stress-strain relationship is slightly affected.

On the other hand, the increase of strength due to the addition of fibers for both compression and tension is noticeable as well as transforming softening of strain into hardening during the undrained test. Lastly, the inclusion of fiber resulted in minimization or elimination of static liquefaction for both compression and extension regardless of the fact that liquefaction in extension requires a higher number of fibers. Noorzad and Amini [5] investigated the effect of randomly distributed monofilament polypropylene on Babolsar sand and found that both fiber content and length showed a crucial positive effect on the required cycle numbers to reach liquefaction. 1% fiber content resulted in the highest liquefaction resistance of 280%. Shear modulus improves with the increase of fiber content as presented in Figure 10 and Table 2.

Lastly, fibers can be useful in reducing or eliminating the lateral movement of soil due to liquefaction. In fact, a summary of the previous works carried out to evaluate the influence of adding synthetic fibers to soil on liquefaction potential is provided in Table 3.

6. Conclusion

This paper intends to review the available studies concerning the inclusion of natural and synthetic fibers on soil behavior in terms of liquefaction occurrence. On the bases of the abovementioned statement, the following points are drawn:

(i) Liquefaction of soil is considered one of the most dangerous and widespread types of ground failures

(ii) Multiple techniques and methods were implemented to evaluate the parameters related to the liquefaction resistance of soil, such as stress-based, strain-based, and energy-based

(iii) Introducing fibers into soil provides many advantages, including enhancing strength characteristics, delay of the tensile crack propagation, and increment in peak shear strength

(iv) The presence of fiber has proved its efficiency in increasing the liquefaction resistance of soil and limiting the generation of excess pore water pressure

(v) The fiber properties, including the type of fiber (natural, synthetic, or waste) fiber content, fiber length, and type of arrangement (randomly or oriented distributed), crucially influence the liquefaction resistance of soils

Finally, the investigation into the inclusion of fibers in soil and its influence on liquefaction resistance has significant real-world applications in geotechnical engineering and construction. The ability to mitigate the effects of liquefaction can lead to improved safety and stability of infrastructure, particularly in earthquake-prone regions. The identification of effective techniques for enhancing soil strength and reducing the risks associated with liquefaction will contribute to the development of more resilient and sustainable construction practices. Furthermore, the utilization of waste or natural fibers as reinforcements can offer additional environmental and economic benefits, promoting more sustainable and cost-effective solutions for soil reinforcement in industry.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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