Liquefaction Characteristics of Sand With Polypropylene Fiber at Low Confining Stress

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The present study evaluates the liquefaction characteristics of Ottawa sand with polypropylene fiber using cyclic triaxial test. A series of stress-controlled cyclic triaxial tests were performed at 34.47 kPa (5 psi) effective confining pressure. Specimens of clean Ottawa sand, and sand containing 0.05, 0.075, 0.1, and 0.3% polypropylene fiber by dry weight of sand were tested at 0.2, 0.25, 0.3, and 0.4 Cyclic Stress Ratio (CSR). Results show a significant improvement in liquefaction resistance when the polypropylene fiber content exceeded beyond 0.075% at 34.47 kPa effective confining stress.

Keywords: sand, polypropylene fiber, cyclic triaxial, liquefaction, cyclic stress ratio

INTRODUCTION

Generally, earthquake damages are depicted based on structural and non-structural failures of superstructures and substructures; but the underlying ground on which a structure is founded has a fundamental role in extents of damage. One of the effects of earthquake to the underlying ground is liquefaction of soil. Liquefaction of saturated soil deposit is an important phenomenon, which governs the behavior of ground and the structure overlying on it. Liquefaction occurs when a saturated soil deposit undergoes significant reduction in strength and bearing capacity when pore pressure rises and equals effective confining pressure due to undrained loading condition created by transient strong shaking during earthquake. Liquefaction phenomenon received major attention after 9.2 Richter scale magnitude earthquake in Nigata, Japan (1964) and 7.5 Richter scale magnitude earthquake in Anchorage, Alaska (1964). In both earthquakes, liquefaction induced damages such as slope failures, bridge and building foundation failures, and floatation of structures were observed (Dobry et al., 1982). In addition, Kramer (1996) also observed liquefaction induced excessive settlement and tilting of buildings. The initial laboratory studies during 1960–80 mainly focused liquefaction of clean sands. However, later, Standard Penetration Tests (SPT), Cone Penetration Test (CPT) to evaluate liquefaction potential revealed that liquefaction may also occur in sands containing fines. This fact was supported by the liquefaction damages that occurred during Central Chile earthquake (1985) (de Alba et al., 1988); Saguenay earthquake (1988) (Tuttle et al., 1990), Superstition hills earthquake, California (1987) (Holzer et al., 1989).

The liquefaction potential is influenced by many parameters, which directly or indirectly affect the behavior of soil, viz. degree of saturation, relative density, earthquake magnitude, ground motion characteristics, fines content, and effective overburden pressure. Several researchers e.g., Seed and Lee (1966), Castro (1969), Youd and Hoose (1977), Ishihara (1984), and Evans and Seed (1987) have investigated the effect of those and several other parameters. Lee and Aurelio (1974), Tatsuoka et al. (1984), Tokimatsu and Seed (1987) have studied earthquake induced settlements and found that significant hazard may result from the dissipation of developed pore

pressure after liquefaction. Meanwhile, several research works are focused on measures to prevent or reduce liquefaction potential. One of the techniques that has gained significant interest is the use of geofibers to improve potentially liquefiable soils. While some research suggests that the use of geofiber in soil improves the static characteristics of sands, and sands with fines, some research works suggest otherwise. On the dynamic characteristics part, Noorany and Uzdavines (1989), and Maher and Woods (1990) observed an increase in soil shear strength and cyclic resistance with the addition of geofibers.

The main purpose of this research is to study the effect of polypropylene fiber on liquefaction characteristics of sand at low confining stress. This study presents the results obtained from cyclic triaxial tests carried out on mixtures of sand with various percentages of polypropylene fibers. The sand-fiber specimens contained 0.05, 0.075, 0.1, and 0.3% of fiber by dry weight of sand. The results from cyclic triaxial tests are evaluated in terms of deformation and pore pressure generation characteristics with respect to application of cyclic loads. The Cyclic Stress Ratio (CSR) for the tests varied from 0.2 to 0.4.

MATERIALS AND METHODS

Materials

The materials used for the cyclic triaxial test specimens are Ottawa 20–30 ASTM C 778 sand and Monofilament Polypropylene fibers. Ottawa sand is naturally occurring silica sand passing through sieve no. 20 (0.84 mm) and retained on sieve no. 30 (0.60 mm) supplied by Humboldt. Quanta chrome gas pycnometer was used to determine the specific gravity of sand tested in accordance with ASTM D5550-14 (2014) and the value was found to be 2.69. The properties of sand are presented in **Table 1.**

The fiber used in this research is Virgin Homopolymer polypropylene monofilament supplied by FORTA corporation, USA. Each fiber is 6 mm in length. These fibers are surface treated with special chemical, which resist moisture and aging. Because of their durability, polypropylene fibers have gained popularity in geotechnical application. The properties of fiber are listed in **Table 2**.

Methods

The maximum and minimum void ratio were determined in accordance with ASTM D4254-16 (2016) and ASTM D4253-16e1

(2016), respectively. The maximum and minimum void ratio of sand was found to be 0.706 and 0.513, respectively. ASTM method 1a was used to perform the test. ASTM D422-63 (2007)e2 (2007) was used to perform sieve analysis of Ottawa sand; and, the grain size distribution was plotted. The sand is classified as poorly graded sand (SP) under Unified Soil Classification System (USCS). The values of D_{10}, D_{30}, and D_{60} were obtained from the particle size analysis graph as 0.48, 0.50, 0.54 mm, respectively. The value of coefficient of uniformity, C_u, and coefficient of curvature C_c were found to be 1.125 and 0.965, respectively.

Sample Preparation

The sand-fiber mixture was prepared by selecting various percentages of fiber by dry weight of sand. The percentage of fibers that were tested in this study were 0, 0.05, 0.075, 0.1, and 0.3%. The fibers were mixed in sand by dry mixing. The fiber strands were separated manually by hand and mixed in sand in small proportions to ensure uniform distribution of fibers within sand. Proper care was taken to avoid segregation of fibers in sand-fiber mixture.

Quanta chrome gas pycnometer was used to determine specific gravity of sand fiber mixture based on ASTM D5550-14 (2014) standard. The tests were repeated until the specific gravity was within standard deviation of 0.005%. The decrease in specific gravity of sand-fiber mix was observed with the increase in percentage of fiber. **Table 3** presents the specific gravity of various percentages of fibers mixed with sand.

Cylindrical samples for cyclic triaxial test had length and diameter of 5.7″ and 2.85″, respectively. The samples were prepared at the relative density of 30% and degree of saturation of 30%. Dry and wet unit weight of samples were calculated by using void ratio, specific gravity, water content, and degree of saturation. The sample was compacted in six layers. Method of undercompaction suggested by Ladd (1978) was used to prepare specimens at constant relative density of 30%.

TABLE 2 | Properties of polypropylene fibers.

Material	Virgin homopolymer polypropylene
Form	Monofilament fiber
Specific gravity (G)	0.91
Tensile strength ksi (MPa)	83–96 (570–660)
Length in (mm)	6 mm
Color	White
Acid/alkali resistance	Excellent
Absorption	Nil
Compliance	ASTM C-1116

TABLE 1 | Index properties of sand.

Property	Values
Specific gravity (G)	2.67
Maximum void ratio, e_{max}	0.706
Minimum void ratio, e_{min}	0.513
D_{10}, D_{30}, D_{60} (mm)	0.48, 0.50, 0.54
C_u	1.125
C_c	0.965
USCS soil classification	SP

TABLE 3 | Specific gravity of sand with various percentages of fiber mixtures.

% Fiber content	0	0.05	0.075	0.1	0.3	0.5	0.75
Specific gravity	2.6688	2.6513	2.6473	2.6471	2.6383	2.6326	2.6130

The height of each layer was then calculated based on the percentage of undercompaction that was needed. The percent of undercompaction for each layer was as follows:

Percent under compaction for nth layer can be calculated using Equation (1) (Ladd, 1978).

$$U_n = U_{ni} - \frac{U_{ni} - U_{nt}}{n_t - 1} * (n - 1) \qquad (1)$$

Where, U_{ni} = Percent under compaction for the first layer

n_t = total number of layer

n = number of layer being considered.

The height of compacted layer is calculated using Equation (2) (Ladd, 1978). The compacted height for bottom most layer was 26.16 and 23.62 mm for all other layers

$$h_n = \frac{h_t}{n_t}(n - 1) + \left(1 + \frac{U_n}{100}\right) \qquad (2)$$

Where, h_t = total height of sample

h_n = height of specimen at the top of the nth layer.

TEST RESULTS

The results and findings of cyclic triaxial test with fiber reinforced sand specimens are presented in this section. First, the details of tests conducted during study are presented in the form of table. Finally, the results of cyclic triaxial test on clean sands and sands with various percentages of fiber i.e., 0.05, 0.075, 0.1, and 0.3% at 34.48 kPa confining pressure have been discussed.

Test Details

In this study, numerous cyclic triaxial tests were carried out in clean sand, and sand-fiber mixtures containing 0.05, 0.075, 0.1, and 0.3% fiber by dry weight of sand. All the samples were prepared at 30% relative density. The samples were tested at 34.48 kPa confining pressure and CSR was varied from 0.2 to 0.4. **Table 4** presents all the tests that had been conducted in this study.

Effect of Fiber on Liquefaction Resistance

To evaluate the effect of inclusion of fiber in Ottawa sand with respect to liquefaction, several tests were conducted on clean sand, and sand containing 0.05, 0.075, 0.1, and 0.3% fiber, respectively. The tests were conducted at 34.48 kPa confining pressure. The initial liquefaction is based on the pore pressure generation criteria i.e., initial liquefaction is considered to have taken place when pore pressure equals the effective confining pressure. In terms of deformation, number of cycles required to trigger 2.5 and 5% of DA strain have been taken into account to compare resistance against liquefaction.

Figure 1 presents a plot of cyclic stress ratio against loading cycles required for initial liquefaction for clean sand and sand containing various percentages of fiber. It can be observed that the initial liquefaction resistance tends to increase and then decrease with the addition of 0.05 and 0.075% fiber, respectively; beyond 0.075% fiber content, initial liquefaction resistance tends to increase with further increase

TABLE 4 | Cyclic triaxial tests on sand-fiber mixtures at initial effective confining pressure of 34.48 kPa.

Sand + fiber % (f)	Dry unit weight (γ_d) kN/m^3	CSR	Remarks
Sand + 0% fiber	15.885	0.2	Did not liquefy (>1,000)
			Liquefied at 511.115 cycles
		0.25	Did not liquefy
			Did not liquefy
		0.3	Liquefied in 14.116 cycles
		0.4	Liquefied in 11.528 cycles
			Liquefied in 3.535 cycles
Sand + 0.05% fiber	15.781	0.2	Did not liquefy
			Did not liquefy
		0.25	Did not liquefy
			Did not liquefy
		0.3	Liquefied in 77.306 cycles
			Liquefied in 75.201 cycles
		0.4	Liquefied in 9.199 cycles
			Liquefied in 6.489 cycles
Sand + 0.075% fiber	15.758	0.2	Did not liquefy
			Did not liquefy
		0.25	Liquefied at 95.142 cycles
		0.3	Liquefied in 39.117 cycles
		0.4	Liquefied in 6.134 cycles
Sand + 0.1% fiber	15.756	0.2	Did not liquefy
			Did not liquefy
		0.25	Did not liquefy
			Did not liquefy
		0.3	Liquefied in 41.256 cycles
			Liquefied in 10.269 cycles
		0.4	Liquefied in 9.233 cycles
		0.4	Liquefied in 9.559 cycles
Sand + 0.3% fiber	15.704	0.2	Did not liquefy
			Did not liquefy
		0.25	Did not liquefy
			Did not liquefy
		0.3	Liquefied in 107.274 cycles
			Did not liquefy
		0.4	Liquefied in 35.162 cycles
			Liquefied in 121 cycles

of fiber content. This may be ascribed to the fact that the voids in the sand-fiber matrix decrease with the increase of fibers which leads to some densification of sand-fiber matrix. Numerically, for initial liquefaction of clean sand, sand containing 0.05, 0.075, 0.1, and 0.3% fiber at 50 loading cycles, it would require CSR values of 0.31, 0.33, 0.30, 0.323, and 0.385, respectively.

Similarly, **Figure 2** presents the graphs of CSR against loading cycles for 2.5% strain. It can be observed that when the fiber content increases beyond 0.075%, the 2.5% DA lines plot higher than 2.5% DA line at 0.05% fiber content. Numerically, CSR values of 0.3123, 0.33, 0.3267, 0.323, and 0.385 would be required
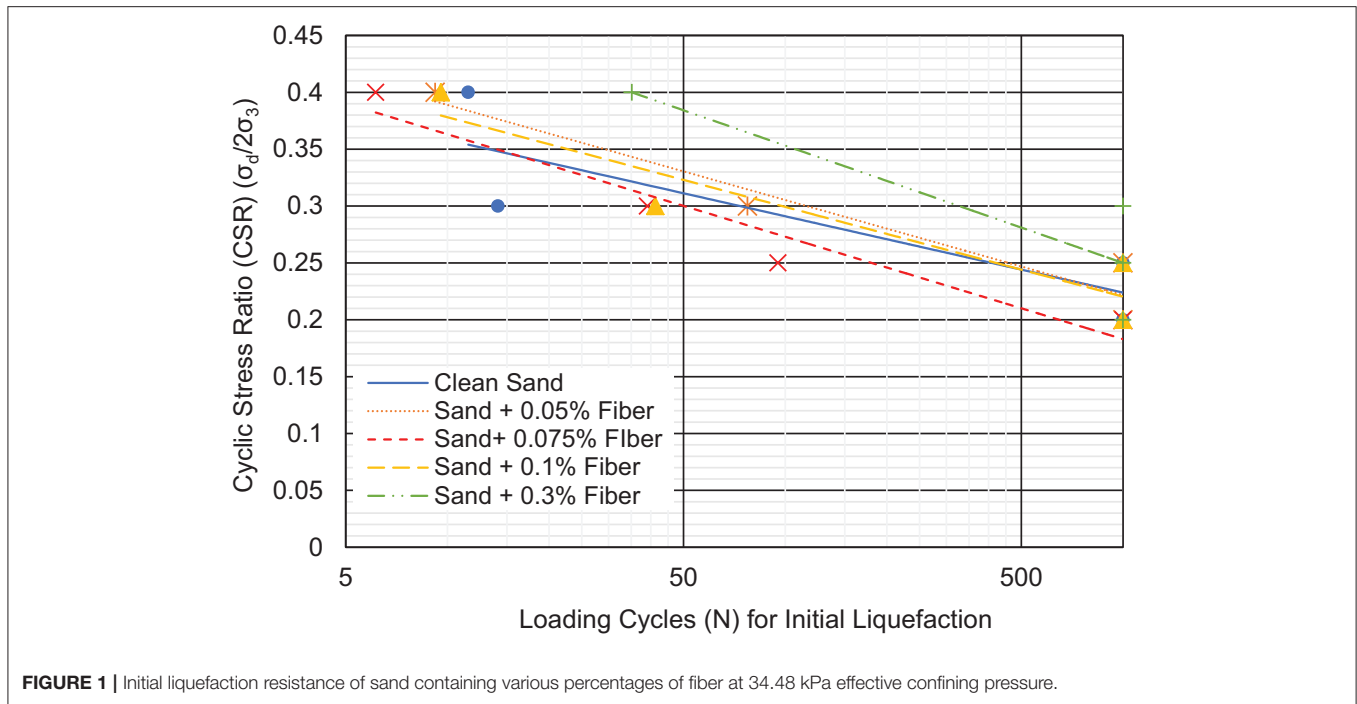
FIGURE 1 | Initial liquefaction resistance of sand containing various percentages of fiber at 34.48 kPa effective confining pressure.
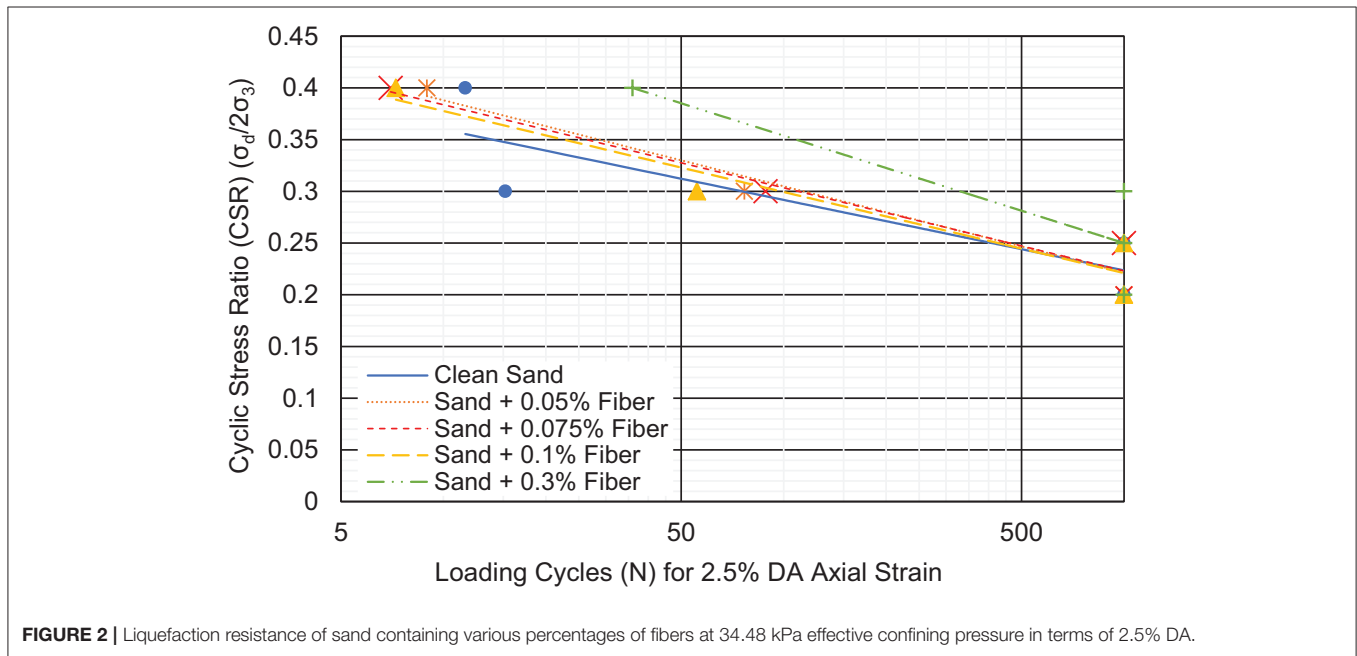

FIGURE 2 | Liquefaction resistance of sand containing various percentages of fibers at 34.48 kPa effective confining pressure in terms of 2.5% DA.

to trigger 2.5% DA strain at 50 loading cycles in clean sands, and sands containing 0.05, 0.075, 0.1, and 0.3% fiber.

Finally, **Figure 3** presents the plot of cyclic stress ratio (CSR) against loading cycles for 5% DA strain. From the **Figure 3**, it can be observed that CSR required to cause 5% DA strain tends to increase and then decrease with addition of fiber up to 0.075% fiber, and consequently, required CSR increases again beyond fiber content of 0.075%. Numerically, it requires CSR values of 0.312, 0.33, 0.3, 0.324, and 0.385, to trigger 5% DA strain 50 cycles

for clean sands and sand containing 0.05, 0.075, 0.1, and 0.3% fiber. The addition of fiber may provide reinforcing effect on sand which is the main reason for increase liquefaction resistance.
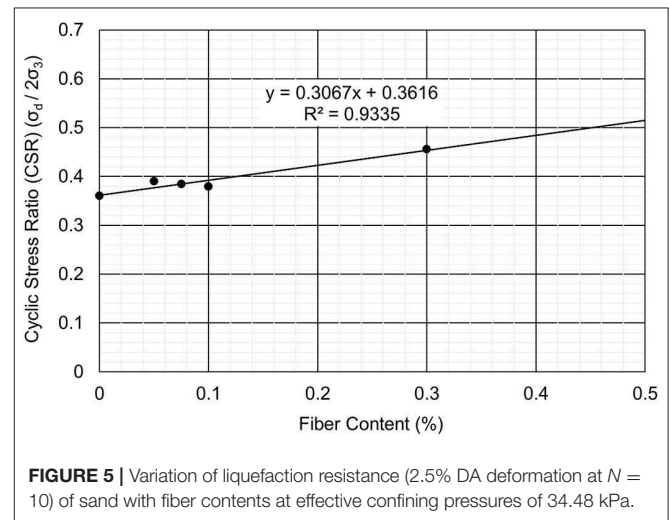
Performance of Fiber

Figure 4 presents the plot of CSR against percentage fiber content for initial liquefaction at 10 cycles at 34.48 kPa confining pressure. It can be observed that for 34.48 kPa effective confining pressure the CSR required for initial liquefaction
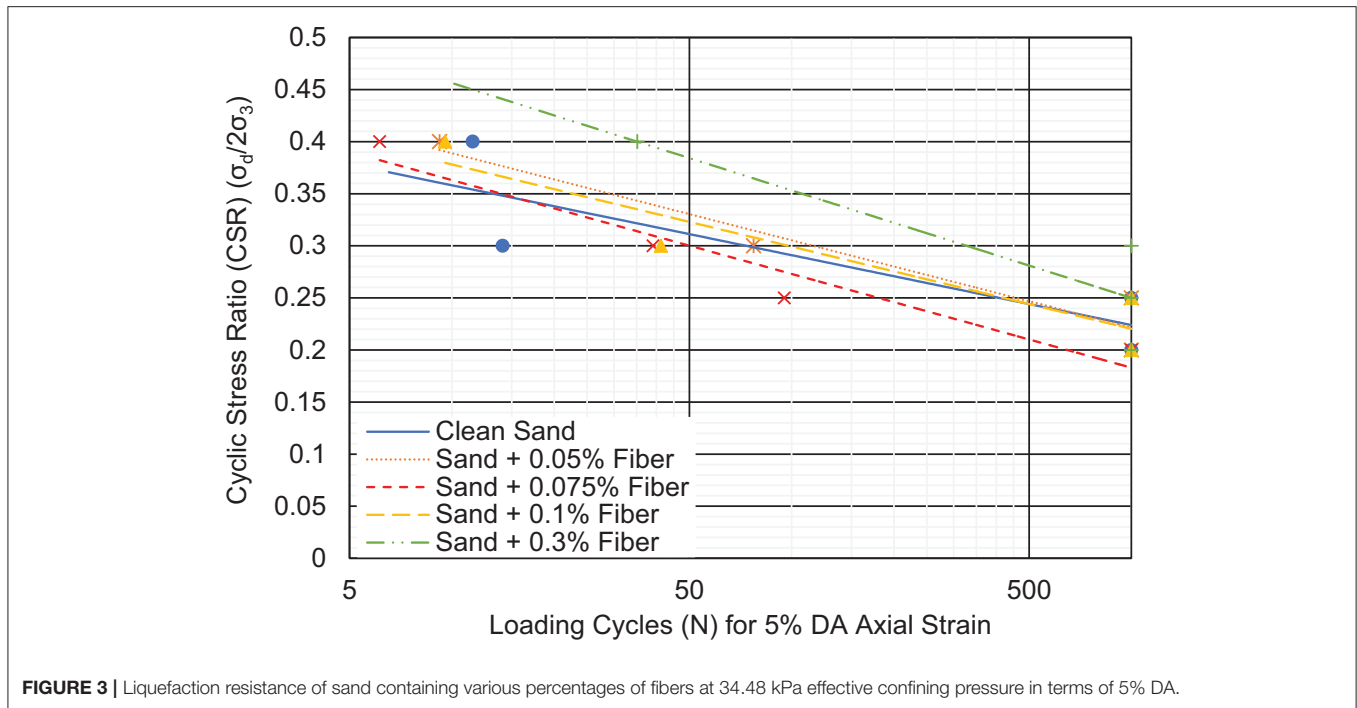
FIGURE 3 | Liquefaction resistance of sand containing various percentages of fibers at 34.48 kPa effective confining pressure in terms of 5% DA.
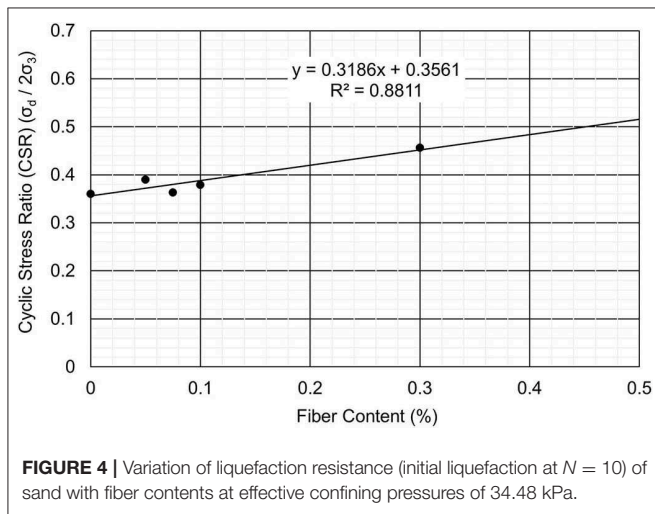
FIGURE 4 | Variation of liquefaction resistance (initial liquefaction at $N = 10$) of sand with fiber contents at effective confining pressures of 34.48 kPa.

FIGURE 5 | Variation of liquefaction resistance (2.5% DA deformation at $N = 10$) of sand with fiber contents at effective confining pressures of 34.48 kPa.
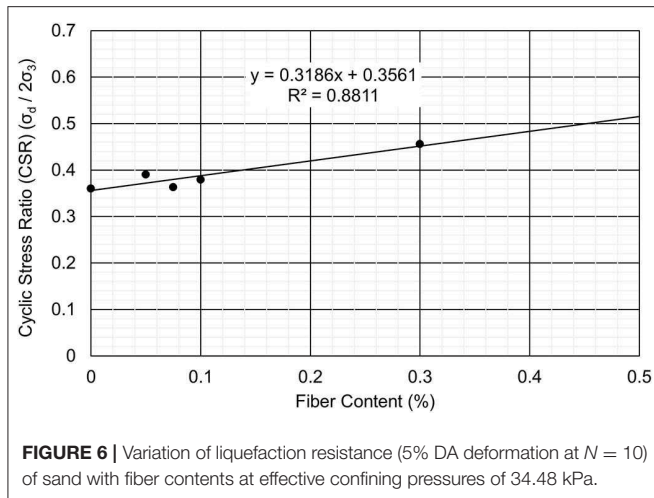
at 10 cycles increases with increment in percentage fiber by dry weight of sand. With further increment of fiber content, the CSR required for initial liquefaction at 0.1 and 0.3% fiber content is 0.4 and 0.458 at 34.48 kPa effective confining pressure.

Figure 5 presents the plot of CSR against percentage fiber content for 2.5% DA strain at 10 cycles at 34.48 kPa confining pressure. It can be observed that for 34.48 kPa effective confining pressure the CSR required for 2.5% DA strain at 10 cycles increases with increase in fiber percentage by dry weight of sand. With further increment in fiber content, the CSR required to get 2.5% DA strain at 0.1 and 0.3% fiber content is 0.4 and 0.457 at 34.48 kPa effective confining pressure.

Figure 6 presents the plot of CSR against percentage fiber content for 5% DA strain at 10 cycles at 34.48 kPa confining pressure. It can be observed that for 34.48 kPa effective confining pressure the CSR required for 5% DA strain at 10 cycles increases with increment in percentage of fiber by dry weight of sand. With further increment in fiber content, the CSR required to get 5% DA strain at 0.1 and 0.3% fiber content is 0.39 and 0.458 at 34.48 kPa effective confining pressure.

Summary

In this study, results of cyclic triaxial test performed on sand and sand containing various percentages of fiber were analyzed and

FIGURE 6 | Variation of liquefaction resistance (5% DA deformation at $N = 10$) of sand with fiber contents at effective confining pressures of 34.48 kPa.

discussed. The specimens comprised clean sand, and sand mixed with 0.05, 0.075, 0.1, and 0.3% fiber by dry weight of sand. To study the effect of cyclic stress ratio (CSR), the specimens were tested at 0.2, 0.25, 0.3, and 0.4 CSR. Also, to identify the effect of confining pressure, specimens were tested at 34.48 kPa initial effective confining pressure. The results for clean sand based on pore pressure generation, 2.5 and 5.0% DA strain were presented first, followed by results of sand specimen containing 0.05, 0.075, 0.1, and 0.3%, respectively. Next, the results discussing the effect of fiber content were presented based on confining stress and cyclic stress criteria.

The results revealed that the liquefaction susceptibility increases with increase in cyclic stress ratio (CSR). For instance, it required fewer loading cycles for all specimens to liquefy as the cyclic stress ratio increased. Next, at 34.48 kPa initial effective confining pressure, the addition of fiber seemed to improve the liquefaction resistance at fiber contents beyond 0.075%. This is evident from the **Figures 1–3**, which shows that the liquefaction

resistance initially decreases with addition of fiber up to 0.075% fiber content beyond which it significantly improves liquefaction resistance. This finding is consistent with the observation made by Noorzad and Amini (2014) on Babolsar sand.

CONCLUSIONS

The present study summarizes the results obtained from number of cyclic triaxial tests conducted on 20–30 Ottawa sand with various percentages of monofilament polypropylene fibers. The tests were undertaken with the aim to investigate the liquefaction characteristics of Ottawa sand with the addition of monofilament polypropylene fibers. Based on the series of cyclic triaxial tests on clean sand and sand containing various percentages of fiber the following conclusions can be drawn:

- For a given confining pressure, the liquefaction resistance tends to decrease with the increasing Cyclic Stress Ratio (CSR).
- The liquefaction resistance of sand-fiber specimen decreases as the cyclic stress ratio (CSR) increases.
- At 34.48 kPa initial effective confining pressure, the liquefaction resistance increased with the fiber content. Resistance to liquefaction was maximum when the fiber content was increased to 0.3%. The resistance to liquefaction in terms of CSR improved by 26% at 0.3% fiber content compared to clean sand.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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