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Liquefaction Response of Geofoam Reinforced Sand

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Abstract. Liquefaction, which is an earthquake hazard caused by undrained cyclic loading, is a phenomenon where a significant portion of the soil's shear resistance is lost as a result of a rise in pore water pressure and starts flowing like a dense liquid. Many studies have been carried out in literature to understand the concept of liquefaction in soils and various mitigation techniques. Expanded Polystyrene (EPS) Geofoam inclusions in geotechnical constructions have gained significant popularity and attention in recent times. EPS geofoam is considered a suitable alternative to conventional sand and gravel backfill materials in geotechnical structures like retaining walls and roads, as it has several beneficial effects like reduction in vibration amplifications due to excellent damping properties and mitigating possible failure because of its significantly low unit weight. Most of the research on geofoam-reinforced soils is focused on characterizations, damping, cyclic loading properties, and shear strength changes. There are no studies available on the liquefaction response of geofoam-reinforced sand. The present study tries to understand the cyclic loading response and liquefaction potential of sand specimens with geofoam inclusions through cyclic simple shear tests. Main findings of this work highlight the efficiency and capability of EPS Geofoam in reducing the excess pore water pressure during cyclic loading and hence help in mitigating liquefaction.

Keywords: Liquefaction, Geofoam, Cyclic simple shear test, Reinforced sand.

1 Introduction

Liquefaction is one of the most devastating phenomena during an earthquake event. It has been extensively studied by several researchers over the years. Mitigation techniques such as ground densification, grouting, and earthquake drains are being widely used across the world. However, these methods are expensive. With the advancement of geosynthetics, many complex geotechnical problems were solved very easily and on a low-cost budget. Recently EPS Geofoam, one such polymeric material, has been used and studied by several researchers for geotechnical problems.

A synthetic polymer with a closed-cell structure, expanded polystyrene (EPS), is used in geosynthetic applications. It is produced by heating expandable polystyrene beads with steam and then pressing the heated beads into moulds to produce prismatic blocks of EPS. Because it weighs less than 10% of other lightweight fill options and only 1% of soil and rock weight, EPS foam offers numerous distinct advantages for usage as a soil substitute. Due to its lightweight, it is an excellent choice for reducing the weight of concrete in bridges, platforms, etc. Additionally, EPS geofoam provides creative solutions for a variety of issues, such as earthquake shock absorption and vibration and noise dampening. When soil conditions are unstable, geofoam provides stability.

The first step in creating EPS geofoam is to steam-treat polystyrene resin beads that contain a hydrocarbon-blowing agent. Pre-puff is created when the polymer softens, and the beads are expanded by the blowing agent. Then, these already-expanded beads are put into big rectangular block moulds. The final result is formed when the beads expand further and fuse together in the moulds after being filled with steam. Geofoam is a block or planar stiff cellular foam synthetic polymer used in geotechnical engineering applications, according to the American Society of Testing and Materials (ASTM). Additionally, it describes expanded polystyrene (EPS) as a kind of foamed plastic created during the moulding process by the expansion of polystyrene resin granules.

In Germany in the early 1950s, EPS geofoam was used for the first time in the construction of pavement as part of a study to determine its viability as a pavement insulator. Despite its effectiveness in this purpose, EPS geofoam was only employed as highway insulation in highlands and mountainous regions wherein harsh winters would necessitate the employment of frost countermeasures. After an assessment by the Norwegian Public Roads Authority, EPS geofoam was later chosen as a lightweight fill material in highway construction. They suggested using expanded polystyrene as a lightweight backfill because their studies revealed that it could endure the recurring pressures which are generally caused by a pavement surface. In the following years, EPS geofoam was effectively used in geotechnical applications across the globe in nations like the US, the Netherlands, Malaysia, and Japan. India and the majority of other emerging nations currently use geofoam inclusions for dynamic loading applications.

By conducting a cyclic unconfined stress-controlled compressive strength test on cylindrical specimens with a density of 19 kg/m^3, implementing various stress levels up to 270,000 load iterations at a frequency range of 3 to 6 Hz, Duskov (1997) approximated the deterioration of the dynamic elasticity modulus. Whenever the deformation caused by the static deviator stress was applied beyond the elastic region, test findings indicated a strong effect of several load repetitions on E_{dyn} and irreversible displacements [1].

In order to calculate damping ratios and shear moduli under various load frequency conditions between 0.01 to 2 Hz, Athanasopoulos et al. (1999) performed resonant column tests on EPS Geofoam samples with different densities. The shear strength rose with density, according to test results, although this parameter had no effect on the damping ratio. The findings of the cyclic test revealed that the shear modulus was not significantly affected by load frequency. The damping ratio did, however, rise with load frequency, suggesting EPS' viscous characteristics [2].

The advantages of geofoam inclusions in geotechnical structures on their response to various earthquakes were presented by Hemanta Hazarika et al. (2001). The Hyogo-ken Nanbu earthquake, which had earthquake motions that were far higher than those of any of the earthquakes that struck the southern region of Hyogo prefecture, is the most noteworthy. In Kobe City, the quake severely damaged a number of infrastructures. However, the EPS embankments installed in these regions demonstrated that there had been little to no significant and direct earthquake-related damage to these buildings [3]. A numerical simulation on a foundation made with EPS geofoam was performed by Daigavane (2014). It was noted that the use of geofoam significantly reduces settling and that it also increases the load-carrying capacity [4].

When EPS geofoam was utilized, Rashid et al. (2017) looked at whether there was a decrease in the lateral earth pressure behind rigid retaining walls. They performed finite element modeling of retaining walls with geofoam filling and investigated the impact of various surcharge loading conditions [5]. According to Notash et al. (2018), adding more geofoam lessens the stresses acting on a cantilever retaining wall. Additionally, it was noted that geofoam with a relative thickness of up to 0.05H (where H is the wall's height) dramatically lowers the retaining wall's toppling safety margin [6]. Geofoam inclusion was explored by Belsare et al. (2019) in order to lessen the lateral earth pressure on piled retaining walls. Geofoam was utilized in a variety of densities and thicknesses. Results revealed that geofoam with a density of 15 kg/m^3 reduced pressure more significantly and that pressure reduction increased with thickness [7].

It is clear that most of the existing studies on geofoam inclusions in soils deal with their dynamic characterizations and their role in reducing earth pressures in retaining walls. There are limited or no studies available on the liquefaction response of soils with geofoam inclusions. Since most pavement structures and retaining walls use granular soils for their construction, liquefaction is one of the potential reasons for their failure during earthquakes. Many case studies all over the world showed that flow liquefaction and lateral spreading are some significant reasons for retaining walls and road embankment failures during earthquakes. Since geofoam is increasingly being used in the construction of these structures, understanding the performance of soils with geofoam inclusions under cyclic loading conditions is a topic of potential interest for the earthquake-resistant design of structures.

2 Materials

2.1 Sand

Artificial Manufactured sand obtained by crushing natural rock is used. A preliminary characterization of the sand was done. The particle size distribution was obtained by performing dry sieve analysis as per IS 2720 (part-4)-1985. The sand was classified as well-graded sand (SW). The index properties of the sand were determined as per IS:2720 (part-3)-1980 and IS:2720 (part-14)-1983. Figure 1 shows a photograph of the manufactured sand used in experiments. Figure 2 presents the particle size distribution curve for the sand, and Table 1 presents the properties of sand.

Fig. 1. Sand used in the study

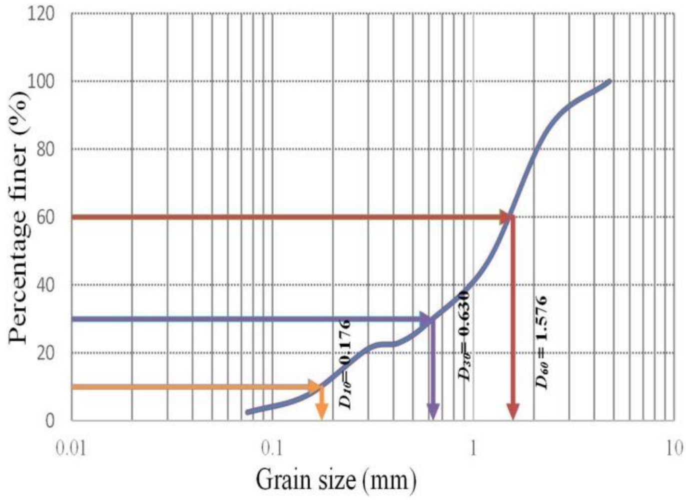

Fig. 2. Particle size distribution curve

Table 1. Properties of sand used for tests.

Property	Value
Coefficient of curvature, C_c	1.429
Coefficient of uniformity, C_u	8.947
Specific gravity, G_s	2.65
Minimum void ratio, e_{min}	0.271
Maximum void ratio, e_{max}	0.563
Minimum dry unit weight (kN/m^3)	16.62
Maximum dry unit weight (kN/m^3)	20.43
D_{60} (mm)	1.576
D_{30} (mm)	0.630
D_{10} (mm)	0.176

2.2 EPS Geofoam

EPS Geofoam blocks of density 30 kg/m^3 (of dimensions 1 m x 1 m x 0.1 m) were procured from a local supplier and were used as reinforcing material in the cyclic simple shear tests. A photograph of the Geofoam sample is shown in Figure 3.

Fig. 3. Photograph of EPS Geofoam

3 Methodology

3.1 Cyclic simple shear test setup

The evaluation of the liquefaction characteristics of non-cohesive soils during cyclic loading can be done using the cyclic simple shear apparatus, which is frequently used for research in the field of soil dynamics. The cyclic simple shear test is substantially better than the cyclic triaxial test in simulating earthquake stress levels. The test specimen is deformed similarly to a soil element subjected to vertically propagating S-waves by applying cyclic horizontal shear forces at the top or bottom of the specimen.

The key benefits of the cyclic simple shear test over the cyclic triaxial test are a good representation of the idealized field stress conditions (plane strain conditions), constant rotation of the principal stresses resulting from the application of shear stress, equivalent to those levied on the soil element in the ground applied to vertically promulgating shear waves, and accurate measurement of shear stress and shear strain. Through a series of simple shear tests, the liquefaction response of geofoam-reinforced sand is investigated in this work. Figure 4 depicts the cyclic simple shear facility used for this investigation.

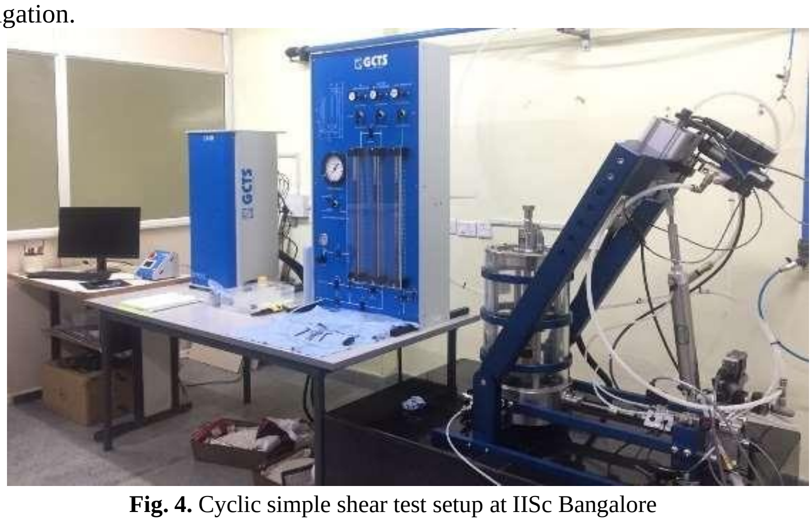

Fig. 4. Cyclic simple shear test setup at IISc Bangalore

3.2 Sample preparation technique

The specimen size in cyclic simple shear tests is 50 mm in diameter and 25 mm in height. The sample is positioned on a pedestal, confined horizontally by a latex rubber membrane secured with O-rings. In order to maintain the diameter of the specimen throughout the experiment, the specimen is restrained by Teflon-coated rings. For the cyclic simple shear test, an EPS geofoam of 8 mm thickness was inserted in the middle of the sample. Figure 5 shows the cyclic simple shear test specimen and the geofoam layer inserted in the middle of the sample.

The predetermined weight of the soil corresponding to 20% relative density was measured and poured into the mould from a predetermined height using the funnel deposition technique. The sample was saturated through the back pressure line, and a Skempton B value of 0.95 was achieved for all the tests, ensuring sample saturation. After saturation, the sample was consolidated at effective confining stress of 100 kPa. Displacement-controlled cyclic simple shear tests of amplitude 4 mm peak to peak and frequency 0.25 Hz were performed under undrained conditions, and the number of cycles to completely liquefy the specimen was recorded, i.e., (when excess pore water pressure ratio, r_u becomes unity).

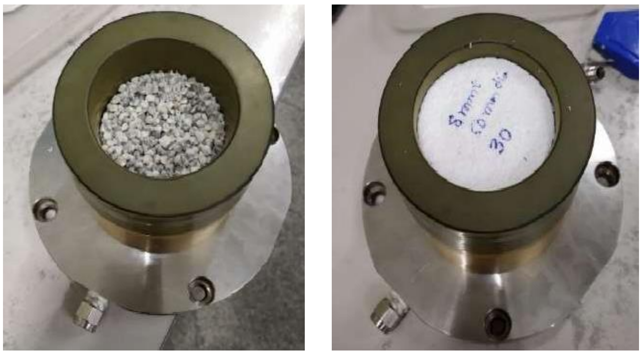

Fig. 5. Specimen with EPS Geofoam inclusion for Cyclic simple shear test

4 Results and discussion

4.1 Unreinforced sand specimen

Test results of the unreinforced specimen are presented in Figure 6. Figure 6(a) shows the applied shear deformation to the specimen. Due to the applied cyclic load on the specimen, the positive excess pore water pressure builds up, and the effective confining pressure decreases continuously. This can be observed in Figure 6(b). As the effective confining pressure on the specimen decreases, its shear strength reduces continuously, as evident in the form of Figure 6(c), where the shear stress reduces continuously. The hysteresis loops of the test are shown in Figure 6(d). Figure 7 shows the development of excess pore water pressure ratio with time. It can be seen that the specimen liquified completely in the 16th cycle as the r_u value reached unity.

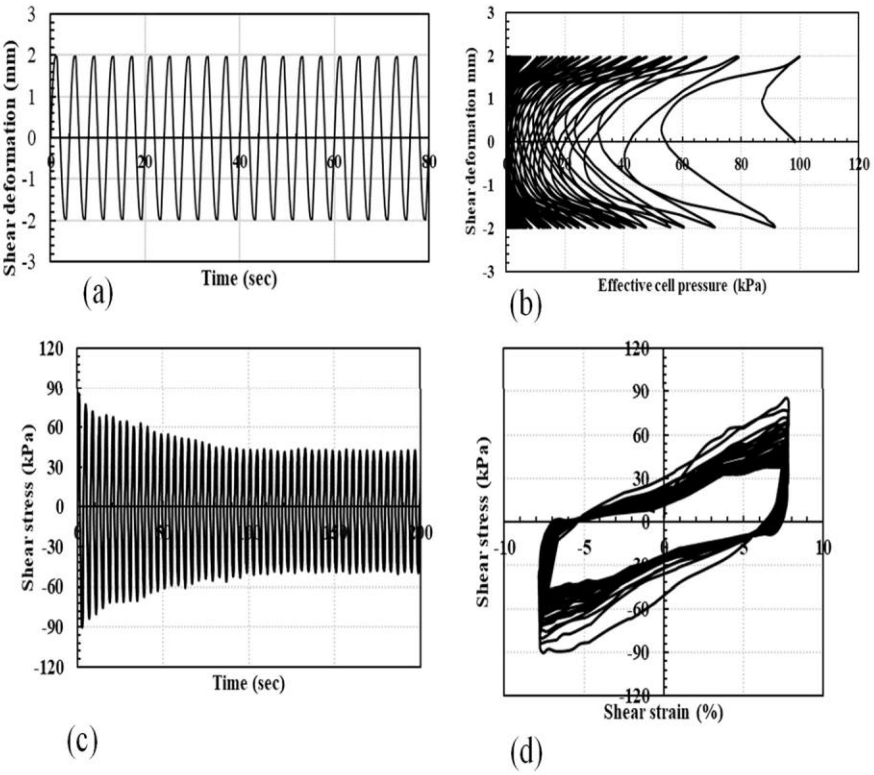

Fig. 6. Unreinforced specimen test results: (a) shear deformation vs. time, (b) shear deformation vs. effective cell pressure, (c) shear stress vs. time, and (d) shear stress vs. shear strain

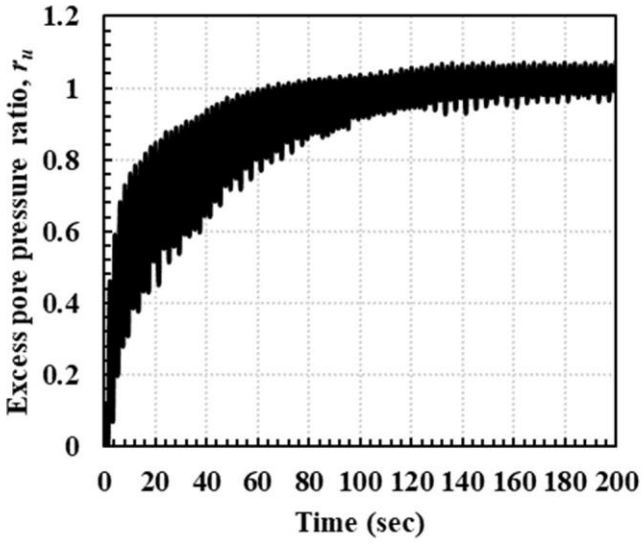

Fig. 7. Excess pore pressure ratio vs. time

4.2 EPS Geofoam reinforced specimen

In the tests with geofoam, an 8 mm thick (1/3rd of the height of the specimen) geofoam disc of diameter equal to the diameter of the specimen (50 mm) was inserted exactly at the center of the specimen. The thickness of the geofoam was kept at 8 mm, which is equal to the one-third height of the specimen. The density of geofoam was 30 kg/m^3. Figure 8 shows the excess pore pressure ratio vs. time for the reinforced specimen. It can be seen that the excess pore pressure ratio reached a value of one (which indicates the complete liquefaction of the specimen) after 184 seconds from the start of the test, which corresponds to 46 cycles as the frequency of loading was 0.25 Hz. It is clear that the reinforced specimen liquified at the 46th cycle, showing an improvement in the liquefaction response of the sand. Geofoam discs exhumed after the test showed no damage, except for the indentation marks of sand particles on the surface, as shown in Figure 9.

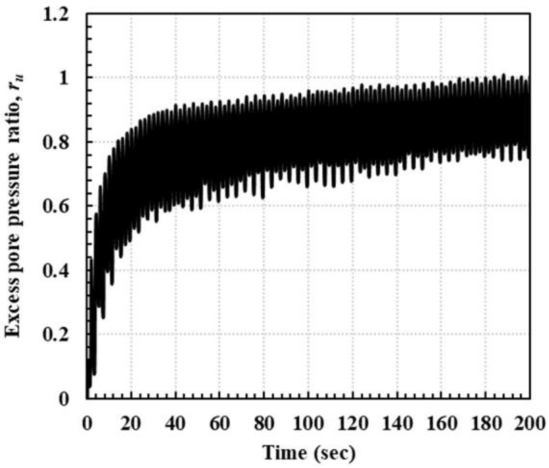

Fig. 8. Excess pore pressure ratio vs. time for reinforced specimen

Fig. 9. Geofoam sample before and after the test

5 Conclusions

Based on the experimental investigation carried out on unreinforced and geofoam-reinforced specimens using cyclic simple shear tests, it is found that the unreinforced specimen liquified in the 16th cycle, whereas the geofoam-reinforced specimen liquified in the 46th cycle, highlighting the potential usage of geofoam in helping to prevent liquefaction in the sand specimens. Thus, geofoam is a potential geosynthetic material that can be used for liquefaction mitigation in sands.

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