Feasibility of rubber–sand mixture columns for liquefaction mitigation: shake table investigation

A. Srivastava
Indian Institute of Technology Madras, Chennai, India, ce20d201@smail.iitm.ac.in

S. Banerjee
Indian Institute of Technology Madras, Chennai, India, subhadeep@iitm.ac.in

ABSTRACT: Rubber sand mixtures (RSM) have emerged as promising materials in various geotechnical applications, including lightweight backfill, embankment construction, and seismic isolation layers. Laboratory element tests reported in the literature consistently highlight their ability to reduce excess pore-water pressure and improve the cyclic resistance of loose sands, thereby mitigating the risk of liquefaction. Despite these encouraging results, the large-scale and in-situ use of RSM for liquefaction mitigation remains relatively unexplored. Previous researchers have examined their performance in roles such as thin-layer drains, rubber-wall type drains, and as protective barriers against pipeline uplift. The present study investigates the feasibility of employing an optimized RSM as a column material for ground improvement in liquefiable soils. A shake-table experiment was performed on groups of RSM columns and, for comparison, on gravel columns of similar particle gradation installed in saturated, loose sand. The test results demonstrate that RSM columns effectively reduce pore pressure build-up and settlement, indicating they can serve as a viable and sustainable alternative to conventional gravel columns for in-situ liquefaction mitigation.

1 INTRODUCTION

During earthquakes, loose saturated sand undergoes contraction, which results in liquefaction due to undrained conditions. One of the most popular solutions to mitigate liquefaction is the introduction of stone columns in the ground. The stone columns will serve the following purposes: (i) increase the density of the surrounding soil, (ii) increase drainage to reduce the rate of development of excess pore water pressure, and (iii) increase the stiffness of the ground to control the settlement of the structure (Kramer, 1996).

On the other hand, the rapid industrialisation accompanied by infrastructure development results in more vehicles hitting the roads, and consequently, the number of scrap tires generated increases. As a result, the problem of disposal of these scrap tires arises, posing a severe problem of stockpiling scrap rubber tires. At the same time, the rubber sand mixture (RSM) with sand is utilized for various geotechnical applications such as highway embankments (Bosscher et al., 1997), lightweight backfill materials(Ahmed and Lovell, 1993), seismic isolation (Dhanya et al., 2019; Tsang, 2008), and liquefaction mitigation (Amuthan et al., 2020). Lately, various researchers have recognized the use of rubber sand mixture in reducing liquefaction mitigation. RSM is utilized in numerous applications that utilize its high liquefaction mitigation properties, such as reducing pipe upliftment (Ecemis et al., 2021), RSM bed below foundation (Dutta and Nanda, 2022), and rubber drainage columns (Bahadori and Farzalizadeh, 2018). Introducing scrap rubber tire and sand mixture (RSM) as filler material in place of regular granular/stone columns seems a potential sector where bulk use of scrap tires can be made possible. Hence, this study focuses on the performance of the RSM column.

2 MATERIAL

River sand was used to model liquefiable ground. Manufactured sand (M-sand), gravel, and granulated rubber were used to prepare the column material. All materials are shown in Figure 1. The grain size distribution of river sand, manufactured sand, gravel, and granulated rubber is shown in Figure 2. Specific gravity, coefficient of uniformity (C_u), coefficient of curvature (C_c), and median size (D_{50}) of all the particles are given in Table 1. Two types of column groups were prepared. One column was made of M-sand with a mixture of gravel in a 50:50 ratio by volume (also 50:50 by weight, since the specific gravity values are the same for the materials), called the gravel column. The other column group consisted of an M-sand and granulated rubber mixture in a 50:50

volume ratio (70:30 by weight), referred to as the RSM column (Rubber-Sand Mixture column). The grain size distribution of the gravel and rubber is kept similar. Hence, mixing both materials to M-sand in the same proportion (50% by volume) provides a column filler material of similar grain size distribution.

Table 1. Properties of used materials.

Material	Specific gravity	C_u	C_c	D_{50} (mm)
River sand	2.65	2.84	0.89	0.57
M-sand	2.77	4.14	1.17	2.00
Gravel	2.70	2.23	1.17	6.40
Granulated rubber	1.12	2.23	1.17	6.40

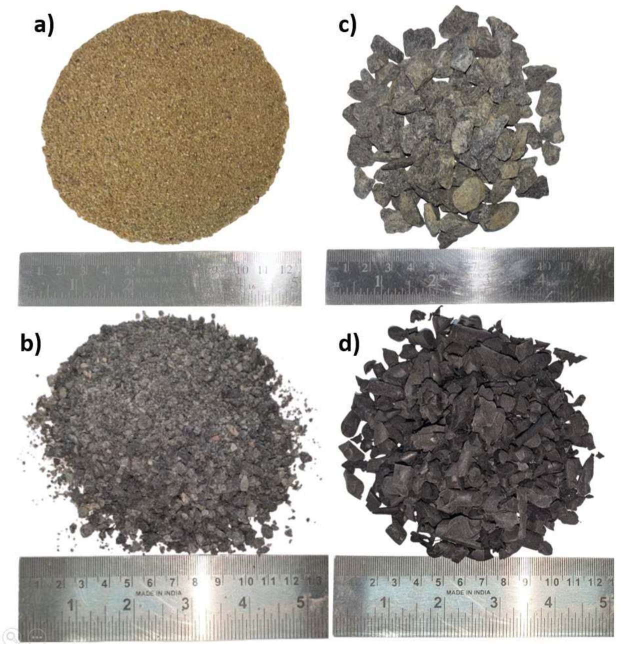

Figure 1. Material a) River sand b) Manufacture sand c) Gravel d) Granulated rubber

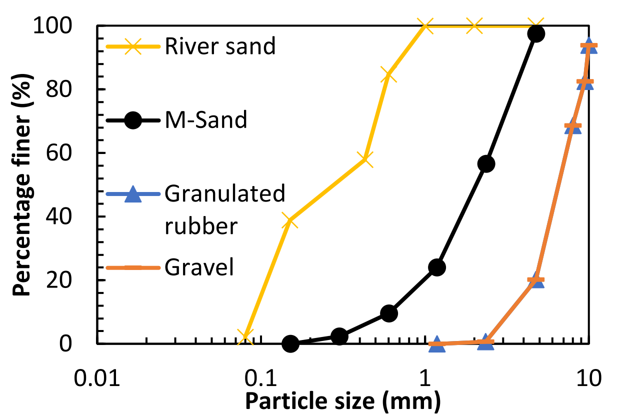

Figure 2. Grain size distribution curve of the material used.

3 METHEDOLOGY

A shake table test has been conducted on a model liquefiable sand with the RSM column group and the gravel column group. A laminar shear box was used for model preparation (Esmaeilpour et al., 2023). Figure 3 shows the prepared model and the shake table machine.

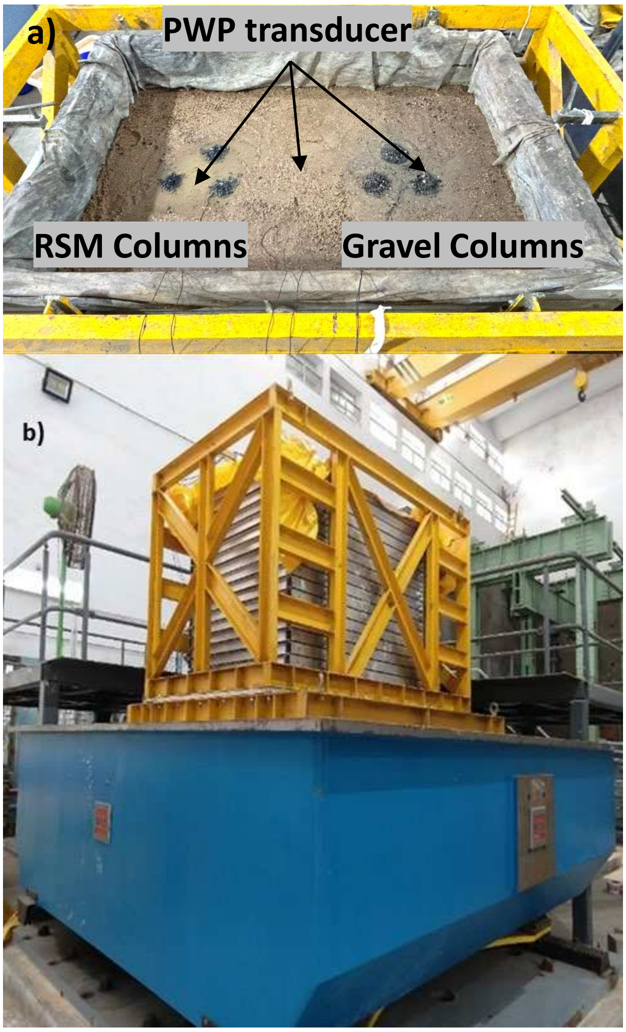

Figure 3. Model setup a) Column groups in liquefiable deposit b) Shake table machine

3.1 Model preparation

The laminar shear box has multiple horizontal frames (laminae) which help it move independently in the horizontal direction. Rollers are placed in between laminae to achieve this. Hence, to prepare a saturated sample, a flexible and leakage-proof sheet is required. A polyester cloth was coated with liquid latex and dried multiple times. The latex-coated sheet was placed in the laminar shear box. Then, a slurry of sand and water was pumped into the shear box to prepare a loose, saturated sand deposit model with a depth of 0.8 meters.

To prepare the column, two groups of three 70-mm-diameter PVC pipes were placed in the shear box prior to slurry pumping. After placing all the river sand in the shear box, the column filling material was placed and tamped, followed by the uplifting of the pipe.

3.2 Sensor validation and placement

A pore water pressure (PWP) transducer, an accelerometer, and a linear variable differential transformer (LVDT) were used to measure the model's response during shaking. A TML company PWP transducer with a capacity of 200 kPa was used. A validation of the calibration (calibration coefficient provided by the manufacturer) was performed by dipping the sensor in water and verifying the value in the sensor reading. The sensor was providing accurate pressure values corresponding to the depth (1 kPa for a 10.2 cm dip).

Three cast iron plates with a thickness of 2.5 cm were placed on the untreated RSM column group and the gravel column group. Accelerometers were placed rigidly on the plate in the direction of shearing. The LVDTs were placed on the top of these plates to measure horizontal settlement. The PWP sensor was placed at a depth of 0.6 meters from the surface. Figure 4 shows the placement of the instruments in the model.

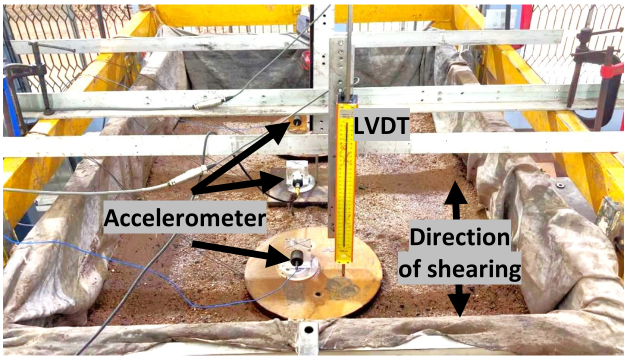

Figure 4. Instrumentation of the prepared model

3.3 Loading and data acquisition

An acceleration time history was applied from the table. The loading was applied in a sinusoidal manner at a frequency of 2Hz. The table acceleration is shown in Figure 5. The HBM data acquisition (DAQ) system was used along with the CATMAN software for data acquisition from the sensor. The data logging was done at a frequency of 200 Hz.

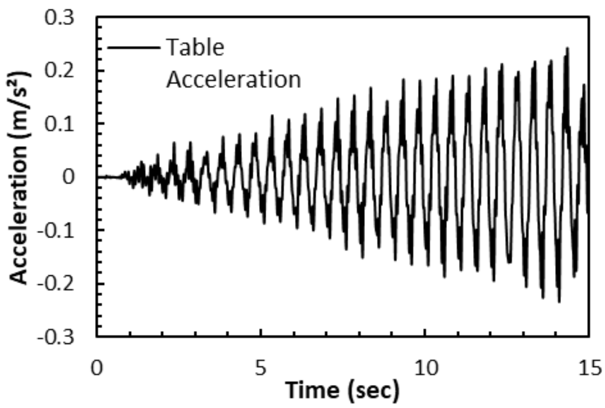

Figure 5. Acceleration time history of the table

4 RESULTS AND DISCUSSION

4.1 Acceleration response

Acceleration time history data were collected from the accelerometers placed on the plates above the treated zone (column groups) and the untreated part (liquefiable ground). Figure 4 shows the Fast Fourier Transform (FFT) of the surface plate acceleration time history in comparison with the input table vibration. The table input acceleration shows a peak at 2 Hz, confirming the application of monochromatic sinusoidal loading. Response spectra of all three configurations at the ground surface exhibit a sharp peak at 2 Hz, indicating that the system's response is governed by the input forced vibration. However, these peaks were higher compared to the table input motion, indicating dynamic amplification of motion as waves propagate upward through the liquefiable soil deposit. Gravel column and RSM column groups show approximately 9% and 7.5% higher peak amplitude (at 2 Hz) compared to the untreated zone, respectively. This indicates a stiffer dynamic response in the column group zone. The slightly lower stiffness offered by the RSM column could be due to additional material damping introduced by the rubber particles.

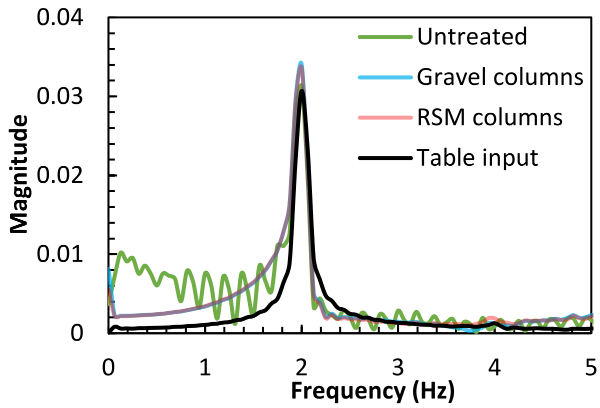

Figure 6. Fourier amplitude-frequency graph

4.2 Excess pore water pressure response

The peak values of the excess pore water pressure recorded from the PWP transducer is illustrated in Figure 7. The figure shows a sudden increase in the excess pore water pressure after 7th cycle, indicating initial liquefaction. It can also be observed that the untreated part of the model shows slightly higher pore pressure generation than the column-treated part. The gravel column zone showed almost the same pore pressure generation compared to the RSM column zone, overall. However, the RSM column zone shows slightly lower pore pressure generation for a few cycles. This indicates that the RSM column group is as effective as the gravel column in reducing pore pressure.

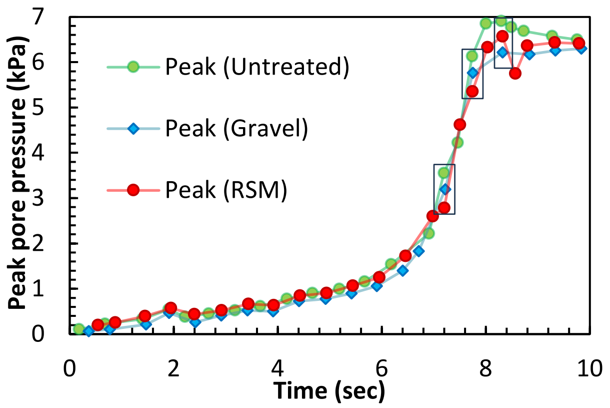

Figure 7. Peak excess pore water pressure readings to PWP transducers

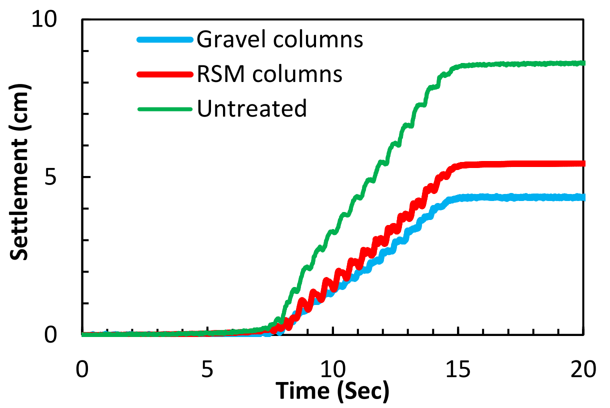

Figure 8. Settlement in the model due to shaking

4.3 Settlement

Settlement data recorded from the LVDT is presented in Figure 8. It can be observed that the gravel and RSM column group zone reduced the settlement by approximately 50% and 40%, respectively, compared to the untreated zone. This indicates that both column groups are very effective in reducing the settlement. However, the gravel column group shows slightly better performance compared to the RSM column group. This could be due to its higher stiffness compared to the RSM.

5 CONCLUSIONS

A shake table test was conducted to compare the performance of a gravel column group with that of a rubber-sand mixture (RSM) column group in reducing liquefaction potential. The results indicate that both column groups are effectively reducing the generation of excess pore water pressure and settlements compared to the untreated liquefiable deposit. However, the gravel column group was able to provide higher settlement reduction compared to the RSM column group. On the other hand, RSM column material provides slightly higher damping. Hence, in cases where the settlement can be compromised to achieve a slight benefit of lower dynamic amplification.

Future tests need to be conducted on a higher area replacement ratio of the column and with different types of loading to further improve the understanding of the effectiveness of RSM columns in liquefiable ground.

REFERENCES

Ahmed, I. and Lovell, C. W. (1993). Rubber soils as lightweight geomaterials. *Transportation Research Record*.

Amuthan, S.M., Boominathan, A. and Banerjee, S. (2020). Undrained cyclic responses of granulated rubber-sand mixtures. *Soils and Foundations* 60, 871–885.

Bahadori, H. and Farzalizadeh, R. (2018). Dynamic Properties of Saturated Sands Mixed with Tyre Powders and Tyre Shreds. *International Journal of Civil Engineering* 16, 395–408.

Bosscher, P. J., Edil, T. B. and Kuraoka, S. (1997). Design of highway embankments using tire chips. *Journal of Geotechnical and Geoenvironmental Engineering* 123, 295–304.

Dhanya, J. S., Boominathan, A. and Banerjee, S. (2019). Performance of Geo-Base Isolation System with Geogrid Reinforcement. *International Journal of Geomechanics* 19.

Dutta, S. and Nanda, R. P. (2022). Waste Rubber–Soil Mat for Protection of Structures from Earthquake-Induced Liquefaction. *International Journal of Geosynthetics and Ground Engineering* 8.

Ecemis, N., Valizadeh, H. and Karaman, M. (2021). Sand-granulated rubber mixture to prevent liquefaction-induced uplift of buried pipes: a shaking table study. *Bulletin of Earthquake Engineering* 19, 2817–2838.

Esmaeilpour, P., Mamazizi, A. and Madabhushi, G. S. P. (2023). An overview of the model container types in physical modeling of geotechnical problems. *Soil Dynamics and Earthquake Engineering*.

Kramer, S. L. (1996). Geotechnical earthquake engineering. *Pearson Education India*.

Tsang, H. (2008). Seismic isolation by rubber–soil mixtures for developing countries. *Earthquake Engineering and Structural Dynamics*. 37, 283–303.