Kochi Chapter

Indian Geotechnical Conference
IGC 2022
15th – 17th December, 2022, Kochi

Effect of Seismic Sequence on the Liquefaction Resistance of Sand using 1-g Shaking Table Experiments

Gowtham Padmanabhan[1] and B.K. Maheshwari[2]

[1] PhD Research Scholar, Department of Earthquake Engineering, IIT Roorkee, Uttarakhand, 247667, India
[2] Shamsher Prakash Chair Professor, Department of Earthquake Engineering, IIT Roorkee, Uttarakhand, 247667, India
bk.maheshwari@eq.iitr.ac.in

Abstract. Occurrence of repeated liquefaction caused severe damage to the foundations and structures (e.g. 2012 Emilia-Romagna seismic sequence). Limited research works have been reported in understanding the mechanism behind the occurrence of repeated liquefaction. This paper presents the mechanism of liquefaction subjected to sequence of seismic events using 1-g uniaxial shaking table apparatus. A rigid watertight container of dimension 1050 mm x 600 mm in plan and depth of 600 mm was used for testing the sand specimen. The specimen was prepared at 25% and 50% relative density and tested under repeated uniform sinusoidal loading conditions. Loading was applied in the sequence of 0.3g (1), 0.3g (2), 0.3g (3) and 0.3g (4) with constant dynamic frequency 5 Hz and 1-minute shaking duration. Excess pore water pressure was measured using the pore pressure transducers at different depths to observe the occurrence of repeated liquefaction. In addition, induced sand densification after each shaking event was estimated. Reliquefaction mechanism was complex and different from that of the liquefaction subjected to independent shaking events. It is found that the effect of preshaking and shaking induced soil densification are critical in influencing the reliquefaction resistance. Despite the obtained beneficial effects of repeated shaking events, pore pressure ratio increases with the successive application of uniform sinusoidal loading events.

Keywords: Liquefaction, Uniaxial shaking table, Sinusoidal loading, Relative density, Preshaking.

1 Introduction

In the recent years, successive seismic events resulted in the repeated liquefaction and associated ground deformations which induced lateral spreading and severe damages to the built infrastructure. Some of the successive seismic events in the recent years include, 2011 Tohoku earthquakes (Japan), 2012 Emilia-Romagna seismic sequence (Italy), 2015 Gorkha earthquakes (Nepal), 2016 Kumamoto earthquakes (Japan), 2018 Lombok earthquakes (Indonesia) and 2019 Vancouver earthquakes (Canada). Past research works mainly focused on liquefaction mechanism and behavior in saturated sand deposits subjected to independent shaking events [1 – 5] and in progress. Maheshwari and Patel [6] reported the influence of non-plastic silts on liquefaction potential of sands and concluded that relative density and level of excitation plays a major role in the generation of excess pore water pressure. Varghese and Latha [7] investigated the factors influencing on the liquefaction resistance of sands through shake table experiments and they found that slight increase in relative density reduces the liquefaction potential of sand to a greater extent. The study also found that the acceleration amplitude and frequency of base shaking reduces the liquefaction resistance of sands. These studies resulted in better understanding of liquefaction phenomenon and appropriate ground improvement techniques were proposed and implemented.

Over the past years, reliquefaction studies attained significance due to its complex and interesting behavior and intricacies in understanding its mechanism. Ye et al. [8] conducted repeated shaking table experiments with different relative densities to investigate the mechanical behavior of liquefaction phenomenon. The authors observed significant increase in density and reduced dissipation time due to the repeated liquefaction-consolidation process. Ha et al. [9] explored the influence of gradational characteristics in the reliquefaction behaviour of sand deposits using repeated shaking table experiments. The study concluded that the single index property or grain characteristic is not sufficient to examine the trends of complex reliquefaction behaviour. Teparaksa and Koseki [10] studied the effect of liquefaction history of soils on reliquefaction resistance with extreme density conditions through shaking table experiments. They concluded that the density alone is not sufficient to define reliquefaction trends as there are several factors influencing the reliquefaction resistance. In order to investigate the reliquefaction behavior of sands Wang et al. [11] carried out shaking table experiments and proposed two dimensional discrete element method. The study focused on the influence of fabric characteristics and concluded that the fabric anisotropy, internal particle arrangement and overall density plays a major role in improving the reliquefaction resistance of sand deposits. Padmanabhan and Shanmugam [12] carried out 1-g shaking table experiments to examine the behavior of reliquefaction phenomenon of sand deposits subjected to sinusoidal incremental acceleration loading conditions. Authors reported that the acceleration amplitude and relative density of the specimen are critical in influencing the reliquefaction behavior of saturated sand specimens. Padmanabhan and Shanmugam [13] investigated the effect of sand densification in enhancing the liquefaction resistance of sand specimen subjected to repeated shaking events. With help of centrifuge modelling experiments, Padmanabhan and Maheshwari [14] presented case study on pre-shaking on reliquefaction potential based on Fukuoka-ken Seiho-oki earthquake, 2005 and Kumamoto earthquake swarm, 2016 and it is important to note that the two earthquakes possess contrasting earthquake history. The study concluded that the effect of pre-shaking influenced by magnitude of foreshocks/aftershocks and liquefaction history and that’s resulted in the increased reliquefaction resistance in Kumamoto region despite several large earthquake events.

Despite the published research works, limited research works has been carried out in understanding the reliquefaction mechanism and behavior of saturated sand deposits subjected to repeated main-shock events. The objective of the present study is to examine the reliquefaction resistance of sand specimen subjected to repeated uniform acceleration loading conditions. A total of 8 experiments was carried using 1-g uniaxial shaking table apparatus by varying the relative density and repeated seismic sequences. Generation and dissipation of pore pressure ratio and shaking induced sand densification was measured and discussed in detail.

2 Experimental Setup and Procedure

2.1 Uniaxial shake table

The experiments were performed on an indigenously fabricated vibration (shake) table available in the Soil Dynamics Laboratory, Earthquake Engineering Department, IIT Roorkee. The shake table was mounted with a rigid mild steel rectangular tank of dimension 1050 mm long, 600 mm wide and 600 mm high. The shake table can produce one-dimensional harmonic excitation of varying amplitude acceleration (0.05 – 1g). The shake table also had facility to change the dynamic load frequency using pulleys of different diameter on the driving shafts. Harmonic excitation with frequency range (2 Hz, 3.5 Hz and 5 Hz) could be produced by the equipment [15, 16]. Three number of pore pressure transducers was used in the study to monitor the generated excess pore water pressure variation during the test at different locations. The location of measuring sensors at three different locations are: 40, 200, and 360 mm from the bottom of the tank for the bottom point (B), middle point (M) and top point (T), respectively. Fig. 1 shows the experimental test setup used in the study.

2.2 Sand

Sand samples was collected from the river bed of Solani river, Roorkee, India. Index properties of Solani sand was estimated in the laboratory. The shaking table experiments will be performed on a poorly graded sand with specific gravity (G) of 2.68, minimum and maximum void ratio of the sample is 0.55 and 0.87 respectively. Other properties of the Solani sand are listed in Table 1.

2.3 Experimental procedure

For experiments, saturated sand specimen was prepared at 25% loose sand density and 50% medium dense sand density. Air pluviation technique was used to prepare the specimen, so as to achieve uniform sand density [17, 18]. Height at which the sand has to be poured to achieve desired sand density was estimated using trial and error method [19]. The sample was prepared to a height of 570 mm. Fig. 2 shows the prepared saturated sand specimen.

A total of 8 shaking table experiments were carried out by varying the relative density. Test series was proposed for stimulating successive main-shock events, where the selected acceleration loading is 0.3g. Dynamic frequency (2 Hz) and 1-minute shaking duration was kept constant for all the events. The selected loading (0.3g) was applied successively four times to the prepared sand specimen. The selected shaking sequence was believed to replicate the 2018 Indonesia earthquake [20]. Five main events were observed within a short interval of time in 2018 Indonesian earthquake justifying the applied 0.3g seismic loading successively four times. The application of continuous incremental acceleration loading will be applied to the ground only after the complete dissipation of generated excess pore water pressure from previous acceleration loading. The rate and time taken for generation and dissipation of excess pore water pressures was monitored continuously using pore pressure transducers. After each shaking event, the soil displacement was measured and corresponding sand density was estimated.

Fig. 1. Experimental test setup

Fig. 2. Prepared sand specimen at desired relative density

Table 1. Index properties of Solani sand

S. No	Property/Characteristic	Value
1.	Soil type (SP)	Poorly graded sand
2.	Specific Gravity of grains (G)	2.68
3.	Uniformity coefficient (C_u)	1.80
4.	Coefficient of curvature (C_c)	1.00
5.	Maximum void ratio (e_{max})	0.87
6.	Minimum void ratio (e_{min})	0.55
7.	Void ratio (e) for D_r = 25%	0.837
8.	Dry unit weight for D_r = 25%	14.09 kN/m^3
9.	Void ratio (e) for D_r = 50%	0.751
10.	Dry unit weight for D_r = 50%	14.78 kN/m^3

3 Results and Discussion

3.1 Effect of pore pressure ratio

A sand specimen is said to be liquefied, if the generated pore pressure ratio (r_u) reaches the value of unity. It is defined as ratio of excess pore water pressure (U) to the effective vertical stress σ'_{vo} estimated at that particular height. In the present study, pore water pressure was measured at three different heights (Top, Middle and Bottom).

Figures 3 and 4 present the variations of generated pore pressure ratio subjected to repeated uniform acceleration loading for 25% and 50% sand density, respectively. It is observed that, for both the density conditions generated maximum pore pressure ratio ($r_{u,max}$) does not reach the value of unity. It means that the soil specimen did not liquefy even under the application of repeated shaking events. However, the pore pressure ratio increases with the repeated shaking events. For e.g. in case of 25% relative density specimen, the reported $r_{u,\,max}$ from the top piezometer reads 0.76, 0.79, 0.83 and 0.85 for the application of 0.3g (1), 0.3g (2), 0.3g (3) and 0.3g (4) respectively.

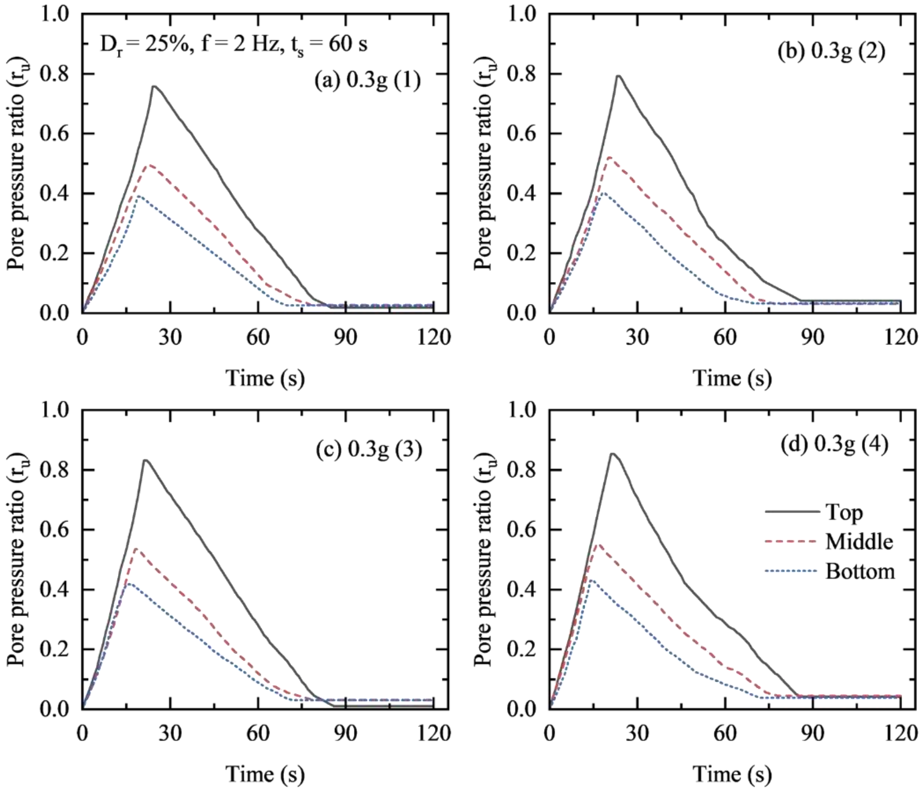

Fig. 3. Variation of generated pore pressure ratio with time subjected to repeated seismic shaking events (D_r = 25%, f = 2 Hz and t_s = 60 s) (a) 0.3g (1); (b) 0.3g (2); (c) 0.3g (3) and (d) 0.3g (4).

Similar observations were also reported for 50% relative density sand specimen. The generated $r_{u,\, max}$ was reported as 0.60, 0.66, 0.71 and 0.74 for the applied repeated shaking events 0.3g (1), 0.3g (2), 0.3g (3) and 0.3g (4) respectively. For e.g. the generated $r_{u,\, max}$ increases to a maximum of 12% and 24% for varying the acceleration amplitude from 0.3g (1) to 0.3g (4) for 25% and 50% sand density respectively in case of top piezometer. Similar percentage increment was also reported for middle and bottom piezometers. However, rate of percentage increment decreases with the increase in repeated shaking events for both the density conditions.

Compared to 25% density specimen, significant reduction in $r_{u,\, max}$ was reported in case of 50% dense specimen. For e.g. reduction in $r_{u,\, max}$ was reported to a maximum of 21% for the first shaking event (0.3g (1)) and a minimum of 13% for the final shaking event (0.3g (4)) for 50% sand density compared to that of 25% dense specimen in case of top piezometer. It is important to note that the initial relative density of saturated sand specimen increases the resistance to liquefaction for both the independent and repeated shaking events.

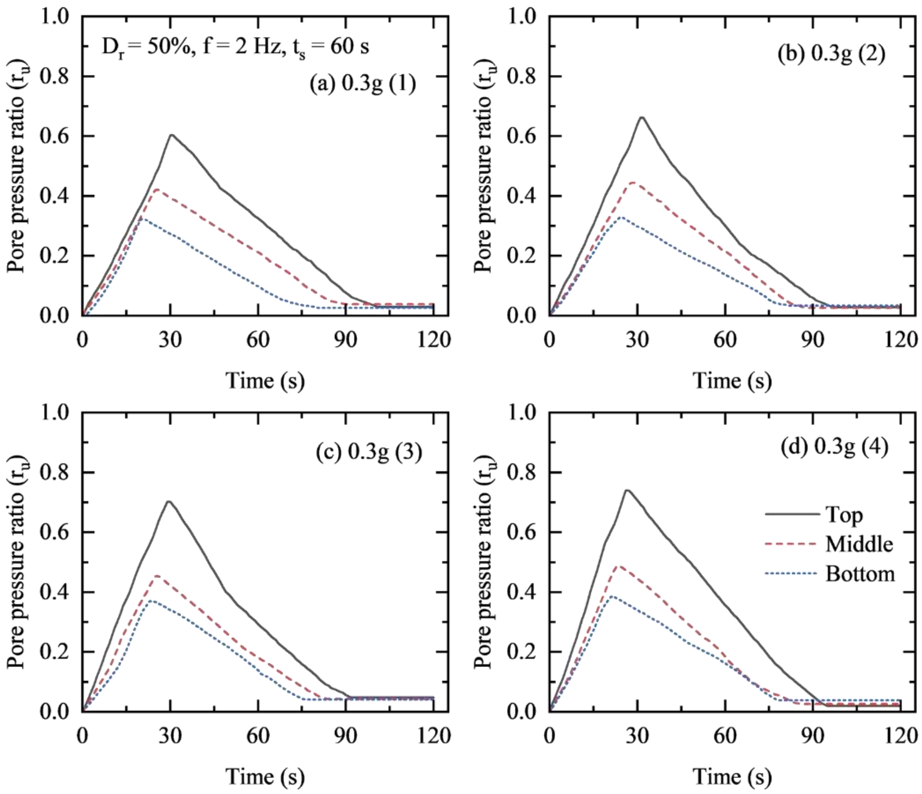

Fig. 4. Variation of generated pore pressure ratio with time subjected to repeated seismic shaking events (D_r = 50%, f = 2 Hz and t_s = 60 s) (a) 0.3g (1); (b) 0.3g (2); (c) 0.3g (3) and (d) 0.3g (4).

As discussed earlier, the generated excess pore water pressure was measured at three different depths. From figures 3 and 4 it is clearly evident that for all the loading events pore pressure ratio was higher for the top piezometer and lower for the bottom piezometer. The pore pressure ratio values lie in median for the middle piezometer. This is due to the lesser effective vertical stress σ'_{vo} due to lower overburden pressure at the top compared to that of the middle and bottom points respectively. This was found applicable to both loose and medium dense saturated sand specimen. Further it is understood that the higher pore pressure ratio generated at the top is the major reason for the failure of shallow founded structures and foundations.

Another important aspect in examining the liquefaction resistance is the time taken to attain maximum pore water pressure ratio. From figures 3 and 4 the time taken to attain $r_{u, max}$ can be seen and it is found that the time taken slightly decreases with the application of repeated shaking events. The time taken to attain $r_{u, max}$ was found higher in case of medium dense sand specimen (50%) compared to that of loose saturated sand specimen (25%). The pattern was found similar for both the density profiles and for all piezometers at different depths. For e.g. in case of top piezometer, the time taken to attain $r_{u, max}$ was reported as 24 s, 23 s, 21 s and 21 s for 25% sand density and 31 s, 30 s, 28 s and 26 s for 50% sand density for 0.3g (1), 0.3g (2), 0.3g (3) and 0.3g (4) respectively. Larger the time taken to attain maximum pore pressure ratio; higher the resistance to liquefaction and reliquefaction events.

3.2 Effect on relative density

After the application of first shaking event (0.3g (1)), the generated excess pore pressure was allowed for complete dissipation. It was further ensured from the initial and final readings of the glass tube piezometers employed to measure pore water pressure. During the process of generation and dissipation of pore water pressure, initial anisotropy got disturbed and resulted in the reorientation of sand grains. As a result, non-uniform sand densification was achieved and settlement in soil sample was reported after each shaking event. The corresponding soil settlement was measured after levelling the specimen without any undulations. Similar procedure was reported for all the remaining shaking events.

From the known values of dry and saturated unit weight of sand and modified specimen volume, the average relative density of the specimen after each shaking event was calculated. Figure 5 shows the variation of relative density after each shaking event for both 25% and 50% sand density specimens. The estimated average relative density for 25% relative density reads 42%, 45%, 47% and 49% after being subjected to 0.3g (1), 0.3g (2), 0.3g (3) and 0.3g (4) respectively. In case of 50% sand density specimen the increased relative density values are reported as 64%, 67%, 69% and 71% after being successively subjected to 0.3g (1), 0.3g (2), 0.3g (3) and 0.3g (4) respectively. The percentage increment in relative density after each shaking event was reported as (68%, 8%, 5% and 5%) and (28%, 5%, 3% and 3%) for 25% and 50% sand density specimen after being subjected to first, second, third and fourth successive shaking events respectively. It can be seen that the first shaking event contributed to the maximum increment in sand density for both the ground density profiles. The reason being that the initially prepared sand specimens are loosely packed and are more vulnerable to densification when subjected to seismic shaking events.

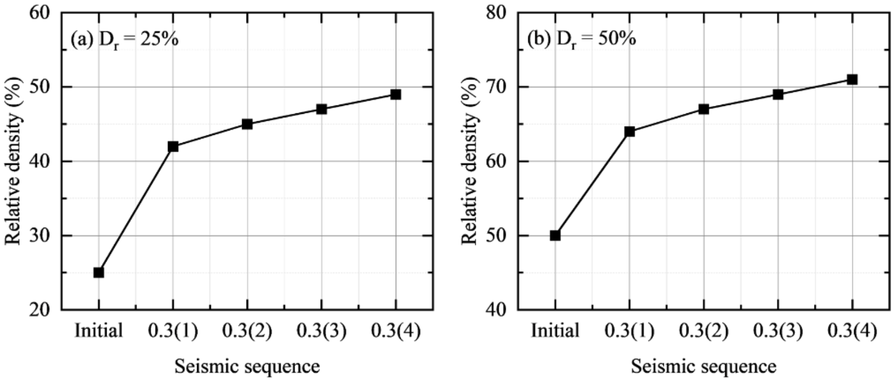

Fig. 5. Variation of relative density subjected to uniform seismic sequence (a) 25% relative density and (b) 50% relative density.

4 Conclusions

1-g uniaxial shaking table experiments were carried out to examine the reliquefaction resistance of saturated sand specimen subjected to uniform successive shaking events. The seismic input parameters were selected as 0.3g acceleration amplitude, 5 Hz dynamic frequency and 1-minute shaking duration. Following conclusions were obtained from the present study,

1. From the experimental observations, it is evident that in a series of main-shock events, the first seismic event is catastrophic and induce significant excess pore water pressure generation. Though, higher pore pressure generated in the successive seismic shaking events, ground deformations were found intense and severe for the first shaking event. The rate of percentage increment in both pore pressure ratio and soil settlement was found lesser with the number of shaking events.
2. The generated pore pressure ratio increases with the number of uniform successive shaking events irrespective of initial sand density. Maximum pore pressure ratio was reported as 0.85 and 0.74 in the top piezometer at the end of the final shaking event (0.3g (4)) for 25% and 50% density profiles respectively. It is clear that, for the applied input motion characteristics, sand specimen could not able to liquefy and reliquefy even under repeated shaking events.
3. Higher the relative density of the specimen, larger the resistance to liquefaction and reliquefaction events. Similarly, the time taken to attain maximum pore pressure ratio was higher for 50% dense sand specimen. Initial sand density found to be critical even under high intense uniform repeated shaking events.
4. The time taken to attain maximum pore pressure ratio slightly decreases with the number of repeated shaking events. This is due to the continuous generation of pore water pressure for each shaking event.
5. The repeated shaking events and dissipation of excess pore water pressure resulted in soil settlement and further increase in relative density of the specimen. Significant increment in sand density was reported after first shaking event for both the density profiles. Whereas, further repeated shaking events slightly contributed to the increment in sand density.

References

1. Seed, H.B. and Lee, K.L. Liquefaction of saturated sands during cyclic loading. Journal of the Soil Mechanics and Foundations Division, 92(6), pp.105-134 (1966).
2. Poulos, S.J., Castro, G. and France, J.W. Liquefaction evaluation procedure. Journal of Geotechnical Engineering, 111(6), pp.772-792 (1985).
3. Polito, C.P. and Martin II, J.R. Effects of nonplastic fines on the liquefaction resistance of sands. Journal of geotechnical and geoenvironmental engineering, 127(5), pp.408-415 (2001).
4. Choudhary, S.S., Maheshwari, B.K. and Kaynia, A.M. Liquefaction resistance of Solani sand under cyclic loads. In Proceedings of the Indian geotechnical conference, Bombay (pp. 115-118) (2010).
5. Zhang, J.M. and Wang, G. Large post-liquefaction deformation of sand, part I: physical mechanism, constitutive description and numerical algorithm. Acta Geotechnica, 7(2), pp.69-113 (2012).
6. Maheshwari, B.K. and Patel, A.K. Effects of non-plastic silts on liquefaction potential of Solani sand. Geotechnical and Geological Engineering, 28(5), pp.559-566 (2010).
7. Varghese, R.M. and Madhavi Latha, G. Shaking table tests to investigate the influence of various factors on the liquefaction resistance of sands. Natural hazards, 73(3), pp.1337-1351 (2014).
8. Ye, B., Ye, G., Zhang, F. and Yashima, A. Experiment and numerical simulation of repeated liquefaction-consolidation of sand. Soils and Foundations, 47(3), pp.547-558 (2007).
9. Ha, I.S., Olson, S.M., Seo, M.W. and Kim, M.M. Evaluation of reliquefaction resistance using shaking table tests. Soil Dynamics and Earthquake Engineering, 31(4), pp.682-691 (2011).
10. Teparaksa, J. and Koseki, J. Effect of past history on liquefaction resistance of level ground in shaking table test. Géotechnique Letters, 8(4), pp.256-261 (2018).
11. Wang, R., Fu, P., Zhang, J.M. and Dafalias, Y.F. Fabric characteristics and processes influencing the liquefaction and re-liquefaction of sand. Soil Dynamics and Earthquake Engineering, 125, p.105720 (2019).
12. Padmanabhan, G. and Shanmugam, G.K. Reliquefaction assessment studies on saturated sand deposits under repeated acceleration loading using 1-g shaking table experiments. Journal of Earthquake Engineering, 26(6), pp.2888-2910 (2022).
13. Padmanabhan, G. and Shanmugam, G.K. Liquefaction and reliquefaction resistance of saturated sand deposits treated with sand compaction piles. Bulletin of Earthquake Engineering, 19(11), pp.4235-4259 (2021).
14. Padmanabhan, G. and Maheshwari, B.K. Case Studies on Preshaking and Reliquefaction Potential for Different Earthquakes in Japan. In Local Site Effects and Ground Failures (pp. 137-144). Springer, Singapore (2021).
15. Maheshwari, B.K., Singh, H.P. and Saran, S. Effects of reinforcement on liquefaction resistance of Solani sand. Journal of Geotechnical and Geoenvironmental Engineering, 138(7), pp.831-840 (2012).
16. Singh, H., Maheshwari, B., Saran, S. and Paul, D. Improvement in liquefaction resistance of pond ash using stone-sand columns. International Journal of Geotechnical Engineering, 4(1), pp.23-30 (2010).

17. Padmanabhan, G., Shanmugam, G.K. and Subramaniam, S. Shaking Table Tests on Liquefiable Sand Deposits Treated with Sand Compaction Piles. In Proceedings of the Indian Geotechnical Conference 2019 (pp. 523-532). Springer, Singapore (2021).
18. Padmanabhan, G. and Shanmugam, G.K. Addressing Influence of Prefabricated Vertical Drains in Liquefaction Resistance Under Multiple Shaking Events. In Soil Dynamics (pp. 203-212). Springer, Singapore (2021).
19. IS 2720 – Part 14: Methods of Test for Soils–Determination of Density Index for Cohesionless Soils, Bureau of Indian Standards, New Delhi (2006).
20. Afif, H., Nugraha, A.D., Muzli, M., Widiyantoro, S., Zulfakriza, Z., Wei, S., Sahara, D.P., Riyanto, A., Greenfield, T., Puspito, N.T. and Priyono. Local earthquake tomography of the source region of the 2018 Lombok earthquake sequence, Indonesia. Geophysical Journal International, 226(3), pp.1814-1823 (2021).