



Liquefaction and reliquefaction resistance of saturated sand deposits treated with sand compaction piles

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Received: 22 February 2021 / Accepted: 31 May 2021 / Published online: 5 June 2021
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Abstract

To mitigate liquefaction and its associated soil deformations, ground improvement techniques were adopted in field to reinforce saturated sand deposits. Sand Compaction Pile (SCP) is one such popular proven treatment to improve liquefaction resistance of sandy deposits. Installation of sand compaction piles improves soil density and rigidity which further enhance seismic resistance against liquefaction and this was well evident from past field observations. However, studies involving SCP performance during repeated shaking events were not available/limited. In this study, using 1-g uniaxial shaking table, a series of shaking experiments were performed on SCP treated and untreated sand deposits having 40% and 60% relative density subjected to repeated incremental acceleration loading conditions (i.e., 0.1–0.4 g at 5 Hz frequency). Parameters such as improvement in soil resistance and relative density, generation and dissipation of excess pore water pressures, maximum observed foundation settlement and soil displacement and variation in cyclic stress ratio were evaluated and compared. Seismic response of liquefiable sand deposits was found to be improved significantly due to SCP installation together with occurrence of continuous soil densification under repeated loading. The experimental observations suggested that SCP can perform better even at repeated shaking events.

Keywords Sand compaction pile · Densification · Uniaxial shaking table · Reliquefaction · Seismic response

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1 Introduction

Soil liquefaction and its associated deformations during earthquake incidence is one of the major threats to the stability of infra-structures. Also, the occurrence of repeated earthquake events (i.e. Christchurch earthquakes 2010 – 2011; Tohoku, Japan earthquakes 2011; Nepal earthquakes 2015; Kumamoto earthquakes 2016; Indonesian earthquakes 2018, etc.) in the past reported soil liquefaction events combined with foundation settlement/failures. Though field evidences highlighting the possible reasons for the occurrence of soil liquefaction and liquefaction; no studies were available in investigating the performance of ground improvement techniques against repeated shaking events. Considering this requirement, performance evaluation of ground treatment technique under repeated shaking events is attempted in this study to verify foundation-soil improvement system interaction under dynamic events.

Sand compaction pile (SCP) improvement system is a most popular and widely adopted ground improvement technique for improving seismic response of liquefiable deposits. The assessment studies carried out by Tokimatsu et al. (1990) on the performance of 3016 numbers of SCP's inferred that, the technique is effective in mitigating liquefaction phenomenon in the site at Tokyo bay, Japan. Similar observations in seismic resistance and the improvement in SPT penetration after SCP treatment were reported by Okamura et al. (2003) for three different liquefiable fields in Japan. The authors reported that, irrespective of area replacement ratio and method of construction, SCP system is found more effective in minimizing liquefaction potential. Through field investigations and undrained cyclic shear tests, Okamura et al. (2006) found that, the liquefaction resistance of SCP treated deposits increased considerably for a slight reduction in degree of saturation irrespective of sand density. Factors such as grain size, pile depth, replacement ratio and distance from the sand pile also influence the saturation of treated sand deposits.

Yamada et al. (2010) reported, occurrence of liquefaction and liquefaction phenomenon during the historic 2011 Tohoku, Japan earthquake which witnessed main-shock and successive aftershock events. Severe damages were incurred to the infra-structures due to repeated strong earthquake events. However, the sites where SCP installed showed improvement in soil resistance against liquefaction and liquefaction. Further, Harada and Ohbayashi, (2017) also investigated the potential of SCP system, prior to earthquake events during 2003 Tokachi-Oki earthquake and 2004 Nemuro Hanto-Oki earthquake, and found limited soil liquefaction and liquefaction occurrence in SCP treated areas compared to untreated deposits.

Instances of repeated earthquakes events (e.g., the main shock and foreshocks/aftershocks) induces occurrence of soil liquefaction i.e., soil liquefied more than once (Tohoku, Japan earthquake 2011). To understand liquefaction and liquefaction phenomenon and to investigate the factors influencing liquefaction behaviour, extensive experimental, analytical and numerical studies were performed in the past by various researchers (Oda et al. 2001; Yamada et al. 2010; Dobry et al. 2015; Fallahzadeh et al. 2019; Darby et al. 2019 among others). Ye et al. (2007) through experimental and numerical investigations observed, quicker dissipation of excessive pore water pressure (EPWP), when the model ground subjected to repeated shaking events, and in turn induces particle reorientation in the ground profile. Further, soil liquefaction was reported in the subsequent loading despite its improvement in relative density occurred due to previous loading. Similarly, Ha et al. (2011) performed repeated acceleration loading on soils having different gradation characteristics and observed that redistribution of sand deposits under repeated

shaking was greatly influenced by grain characteristics. Further, Ha et al. (2011) stated, once initial sand fabric got destroyed during the first liquefaction event, then void ratio becomes a reliable parameter than relative density in assessing reliquefaction resistance for any sand deposits. Using centrifuge experiments, El-Sekelly et al. (2016) discussed the effect of pre-shaking on liquefiable deposits and compared the test results with field observations. They concluded that, intensity of successive seismic shaking plays a vital role in initiating reliquefaction and also influences the beneficial effect of pre-shaking in generating excess pore pressures. Studies related to the effect of reliquefaction at mesoscopic level were carried by Ye et al. (2018) through 1-g shaking table experiments. The experiments were performed with successive identical input motions with varying shaking duration. The study revealed that, non-uniformity soil deposition resulted in reduction in reliquefaction resistance despite of improvement in relative density similar to Ye et al. 2007.

This study discusses the performance of Sand Compaction Pile (SCP) system in mitigating liquefaction and reliquefaction phenomenon. To assess the performance of ground improvement system, 1-g uniaxial shaking table experiments were carried on untreated and SCP treated saturated ground. For testing, saturated ground having 40% and 60% density was prepared and subjected to repeated shaking events (i.e., 0.1 g, 0.2 g, 0.3 g and 0.4 g at 5 Hz frequency representing low to high intensity shaking events). To evaluate SCP performance, four SCP's having diameter 111 mm and length 600 mm were installed in square pattern with an improvement ratio of 3% and tested at repeated shaking events. The beneficial effect of the selected improvement system was evaluated in terms of pore water pressure response at different depths, improvement in soil resistance and ground density, foundation settlement, soil displacement assessment and estimated cyclic stress ratio parameters. Finally, the effect of SCP induced ground densification mechanism in improving liquefaction and reliquefaction resistance is discussed.

2 Material and apparatus

2.1 Sand

Locally available sand from Solani river bed (Roorkee, India) is used for conducting experimental investigations. The selected soil region lies in seismic zone IV as per Indian standard codal provisions (IS 1893 (Part I)–2016). From grain size distribution, the Solani sand is found to be poorly graded (SP) (IS 2720 Part 4–1985) and lies within the range of liquefiable soils as suggested by (Tsuchida 1970; Xenaki and Asthanapoulos, 2003). The grain size distribution curve and index properties of solani sand were given in Fig. 1 and Table 1 respectively.

2.2 1-g shake table

The laboratory experiments were performed on a uniaxial 1-g shaking table available at Geotechnical engineering division, CSIR–CBRI, Roorkee, India. The dimensions of the shaking table unit are 2 m×2 m having 3 T capacity. The horizontal movement of the table can be formed using a servo-hydraulic actuator attached to the shake table. The maximum peak velocity, maximum stroke length, operating frequency and acceleration range are 2 m/s, 80 mm, 0.01–50 Hz and 0.001–1 g, respectively. The acceleration and dynamic load frequency can be selected as per testing conditions using digital controlled data acquisition

Fig. 1 Grain size distribution curve of sand used for tests (After, Xenaki and Asthanapoulos 2003)

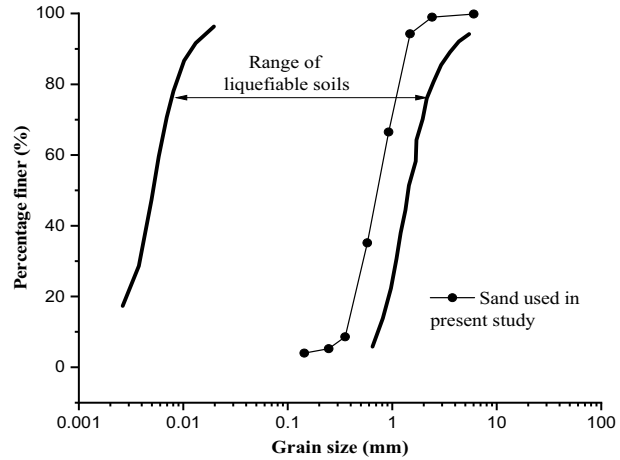


Table 1 Index properties of the test sand

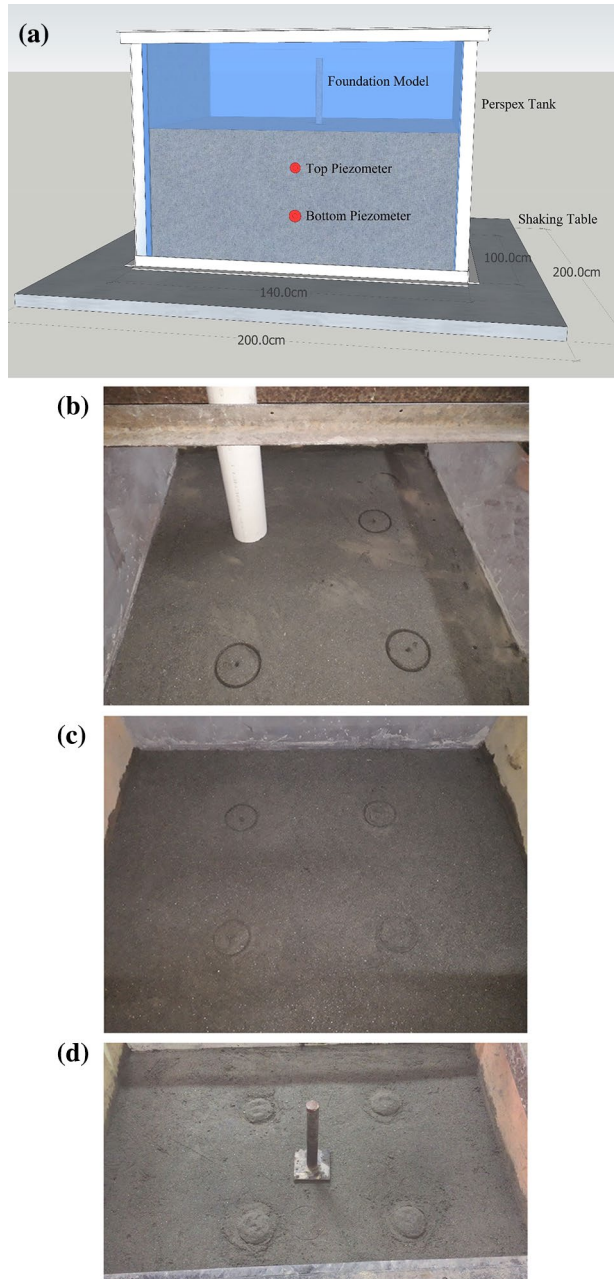
Test sand	Grain sizes (mm)		Coefficient of uniformity, C_u	Specific gravity, G_s	Dry unit weight (kN/m^3)		Void ratio	
	D_{10}	D_{50}			Max	Min	Max	Min
Solani	0.09	0.23	2.63	2.67	17.66	15.66	0.87	0.64

system. The schematic diagram of the experimental setup and instrumentation of sensor was shown in Fig. 2a.

2.3 Digital static cone penetrometer

Digital static cone penetrometer (DCPT) was used for estimating the relative density of prepared ground bed. The penetrometer consists of a driving cone having 60° angle having area of 1.5 cm^2 . The DCPT is connected to an extension rod and having digital display unit at the end. Using digital display unit, the penetration resistance at different depth is measured. For penetration resistance measurement, the penetrometer is pushed continuously in to the prepared ground at the rate of 10 mm/s to 20 mm/s (IS 4968 (Part –III)–1976 and ASTM D3441–(2016)). DCPT was performed at 5 different locations (i.e., 4 points adjacent to sand compaction piles and 1 at centre below foundation) and the average cone penetration resistance was considered. From the obtained cone penetration resistance, relative density of the sand deposit was estimated.

Fig. 2 Experimental setup and Installation of SCP system **a** Schematic diagram of the experimental setup; **b** Selection of location for installation; **c** Completed SCP system; **d** Foundation model embedded in treated ground



3 Experimental procedure

3.1 Sand-bed preparation

A rigid transparent model tank of dimensions $1.4 \text{ m} \times 1 \text{ m} \times 1 \text{ m}$ was fabricated and used for shaking table experiments. The model tank was made with a thickness of 20 mm using Perspex glass and fixed firmly using steel angles with a steel frame. To minimize boundary effects, 50 mm thick polyurethane foam was attached to both sides of tank in shaking direction (Ye et al. 2018; Padmanabhan and Shanmugam, 2020). The bottom surface of the model tank was made rough by sand blasting technique for simulating real field conditions. Generally, the liquefaction response of the saturated sand deposits is highly influenced by the method of sample preparation (Mullins et al. 1977; Tatsuoka et al. 1986). Hence, based on literature studies, wet sedimentation method was adopted for sample preparation since this method proven to be effective in achieving uniform relative density and for simulating natural sand deposition behaviour (Ye et al. 2007; Hamayoon et al. 2016; Bahmanpour et al. 2019).

For experimental studies, saturated sand bed having 600 mm depth was prepared with 40% and 60% density. The quantity of sand and water required to achieve 40% and 60% ground density is estimated prior and collected. The calculation and preparation procedure were same as discussed by Padmanabhan and Shanmugam (2020). The ground bed was divided in to three layers to achieve uniformity in density. Water was filled initially inside the tank for the calculated first layer. Followed by water, sand was then poured in to the tank. To facilitate the free fall and for uniform distribution, an adjustable conical hopper with a 60° inverted cone at bottom is exclusively fabricated and used. The height at which the sand grains to be poured to achieve relative density is evaluated as per IS 2720 (Part XIV)–2006. Thus using wet sedimentation technique, the ground having 40% and 60% density simulating liquefiable saturated sand deposit was prepared. The prepared sand bed was left undisturbed for 24 h to obtain uniform saturation and deposition. To monitor pore pressure generation and dissipation, glass tube piezometers were used for the study. The glass tube piezometers were placed in middle of the ground bed at 0.2 m (B) and 0.4 m (T) height from base of the tank. The mouth of the piezometers was covered with porous stones and wrapped with filter papers, so as to avoid choking of sand particles. The generation and dissipation of excess pore water pressure was monitored continuously till the dissipation of EPWP.

3.2 Installation of sand compaction piles

To simulate real field conditions, Sand compaction piles (SCPs) were installed into prepared saturated sand bed similar to the procedure adopted in field (Harada and Ohbayashi, 2017). Polyvinyl chloride (PVC) pipe was used as a casing pipe for constructing SCP system. A total of four SCPs with a diameter of 111 mm and 600 mm height (improvement ratio of 3%), were installed in square pattern with *c/c* of 450 mm in the sequential manner. The spacing was estimated based on the guidelines provided by Barksdale (1987). The improvement ratio was defined as the total sectional area of sand compaction pile (improved area) to the total area of the model tank (Kitazume, 2005). Square pattern installation was adopted in this study, as it found effective in improving the relative density of sand deposits for replacement/improvement ratio less than 13% (Hossain et al. 2020).

Stages of SCP installation is shown in Fig. 2 and the installation procedure is as follows,

- (1). Positioning:). The location of the SCPs was marked in the prepared ground for excavation. PVC pipes having open end at both sides was used for casing and positioned at the selected location (Fig. 2b).
- (2). Penetration of a casing pipe: PVC casing pipe was pushed to entire depth i.e., 600 mm using vibratory drop hammer. Verticality of PVC pipe was ensured using horizontal steel angle, which was placed and restrained on both sides of PVC pipe. This procedure was shown in the Fig. 2b. The confinement provided by the steel angle not allowed the PVC pipe to deviate from the position, when the impact force was applied.
- (3). Excavation of sand: Using specially designed soil auger, the sand inside casing pipe was removed.
- (4). Pouring of sand: Pre-calculated amount of Solani sand was poured inside the casing pipe in three layers. Using a tamping rod, soil was compacted for each layer for achieving desired relative density (80%). All four SCPs were constructed sequentially for a density of 80%.
- (5). Removal of casing pipe: Casing pipe is slowly lifted, after completion of each compacted sand layer. Utmost care has been taken for smooth withdrawal of the PVC pipe without causing disturbance to the surrounding soil.
- (6). Completion: Same procedure is repeated for all the four SCP system and shown in Fig. 2c.

The improvement in density of the prepared ground i.e. 40% density and 60% density with and without SCP installation was verified using cone penetrometer equipment. The penetration resistance values for every 100 mm depth were measured with and without SCP installation and the results are discussed in Sect. 4.1.

3.3 Foundation model

To study the effect of ground improvement-foundation interaction under repeated shaking events; scaled down shallow footing model was used in this study. The footing was embedded at center inside the prepared ground and settlement response during repeated shaking conditions was assessed. For scaling, dynamic similitude laws proposed by Moncarz and Krawinkler [1981] was adopted in present study and shown in Eq. 1.

$$N_{(EI)} = N_{(K)} \times N_{(L)}^3 \quad (1)$$

$N_{(EI)}$ is the scale factor for flexural rigidity, $N_{(K)}$ is the stiffness scale factor, $N_{(L)}$ is the scale factor for linear dimensions. A scale factor (N) of 10 was adopted and the foundation model with dimensions 115 mm × 115 mm × 30 mm was fabricated. The settlement of foundation model was measured after each shaking event. Similarly, for monitoring soil displacements, settlement plates were placed over the ground surface. After complete dissipation of generated pore water pressures from each shaking event; both foundation settlement and soil displacement for the treated and untreated soil deposit was measured and compared. Foundation model embedded in the SCP treated ground was shown in Fig. 2d.

3.4 Loading conditions

In physical modelling studies, either reduced scale earthquake motion or sinusoidal wave motion was preferred to study the response of saturated ground deposits (Olarde et al. 2017; Ye et al. 2018; Wang et al. 2020). To simulate repeated shaking events, sinusoidal motions having incremental acceleration loading was selected and applied sequentially in this study. The occurrence of liquefaction and reliquefaction with and without treatment was assessed. The selection of repeated shaking was based on repeated foreshock and/or after-shock events associated with main-shock incidence observed during earthquake loading in the past. For experimental testing, sinusoidal acceleration loading having 0.1 g, 0.2 g, 0.3 g, and 0.4 g intensity was selected and applied. The selected acceleration time history employed in this study is similar to Padmanabhan and Shanmugam (2020) simulating low to high intensity of shaking. Further, frequency and shaking duration were kept constant as 5 Hz and 40 s respectively, to examine the influence of longer shaking duration and frequency in influencing seismic response of soil deposit (Yasuda et al. 2012).

The repeated incremental loading was applied to both SCP treated and untreated ground after complete dissipation of excess pore water pressure (EPWP) generated during previous loading i.e. after application of 0.1 g acceleration loading, the time taken for generation and dissipation of EPWP was monitored continuously through glass tube piezometers. After complete dissipation of generated EPWP, subsequent acceleration loading of 0.2 g was applied. The same was repeated for 0.3 g and then to 0.4 g acceleration loading. The variation in soil density, EPWP response, foundation settlement and soil subsidence and cyclic stress ratio at repeated loading conditions were observed for each acceleration loading and the influence of these parameters were discussed in following sections.

4 Experimental results and discussion

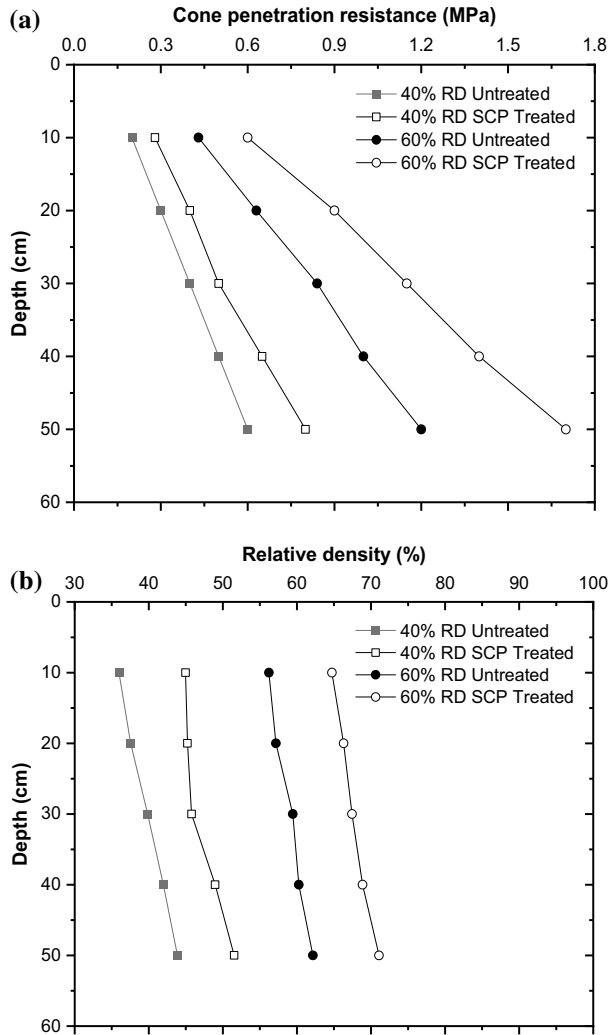
4.1 Effect of ground conditions on liquefaction and reliquefaction resistance for untreated and treated sand deposits

In this section, the effect of in-situ ground density and its response under repeated loading conditions with and without treatment is discussed. The uniformity in ground preparation with depth for 40% and 60% ground is evaluated using a digital cone penetrometer. Similarly after installation of sand compaction piles and application of repeated acceleration loading; the variation in penetration resistance with depth was also assessed. From the obtained penetration resistance, the density of the ground was estimated. The penetration resistance at every 100 mm depth and corresponding relative density was estimated using Eq. 2 proposed by Jamiolkowski et al. (2003).

$$D_R = 100 \left[0.268 \times \ln \left(\frac{q_t / \sigma_{\text{atm}}}{\sqrt{\sigma'_{\text{vo}} / \sigma_{\text{atm}}}} \right) - 0.675 \right] \quad (2)$$

D_R is the relative density of the sample in percentage, σ'_{vo} is the effective overburden pressure (kg/cm^2) and q_t is the cone penetration resistance (kg/cm^3). The variation in density before and after treatment and after application of sequential acceleration loading is discussed in the following sections.

Fig. 3 Initial prepared ground conditions for SCP treated and untreated (UT) soil **a** Cone penetration resistance; **b** Relative density (RD)

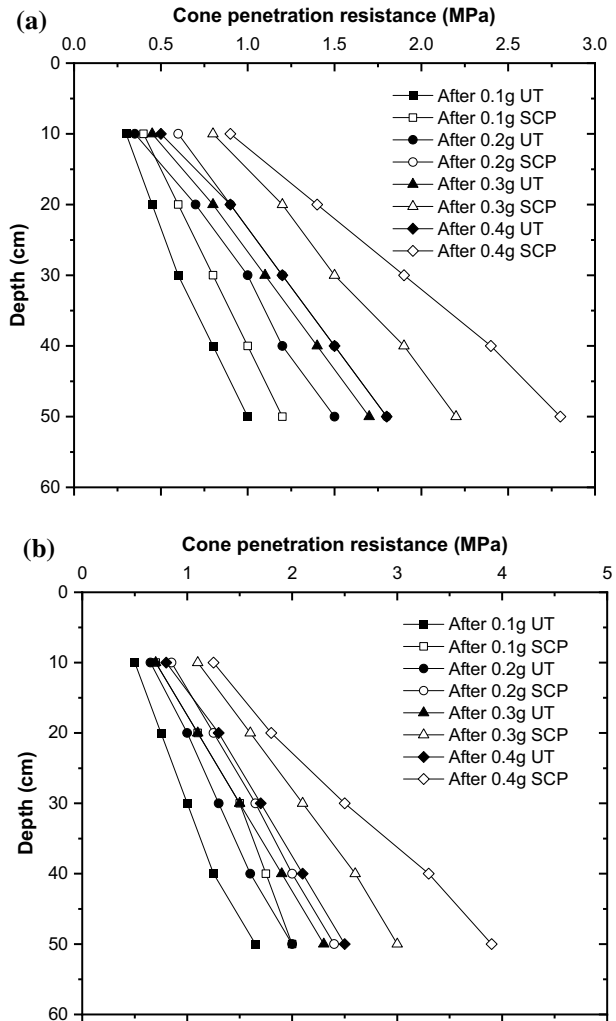


4.1.1 Variation in ground condition due to installation of SCPs

The obtained cone penetration resistance and estimated density of the untreated and treated ground bed having 40% and 60% density is shown in Fig. 3 a, b respectively. Inclusions of sand piles increased the penetration resistance of sands, and are higher at the bottom due to overburden effect, irrespective of initial density and improvement work. It is evident from the Fig. 3b that, wet sedimentation technique induced uniformity in sample preparation. The relative density of ground with depth after sample preparation is between 36 and 42% for 40% ground conditions and 57% to 62% for 60% ground conditions. The slight variation in relative density with depth as seen in Fig. 3b may be due to the overburden effects induced by the top soil layers. However, the variation in density with depth both for 40% and 60% prepared ground found within 5% suggesting that ground is uniform with depth. The effect of SCP installation on 40% and 60% density ground is also plotted on 3 (a) and

(b) for better comparison. It can be seen that, density of the ground improved after installation of sand compaction pile system. For the SCP treated ground, the density increased between 46 to 53% and 65% to 70% for 40% and 60% relative density respectively. Overall, the percentage improvement with depth is in the range between 15 and 17% for both the ground conditions and found similar to real field situations (Hatanaka et al. 2008). As discussed, the installation of SCP system improved both density and rigidity of the saturated ground. This improves the seismic response of liquefiable deposit during dynamic loading conditions. However, the improvement in density induced by the SCP system during repeated shaking events and its influence on liquefaction and reliquefaction resistance is discussed in the following section.

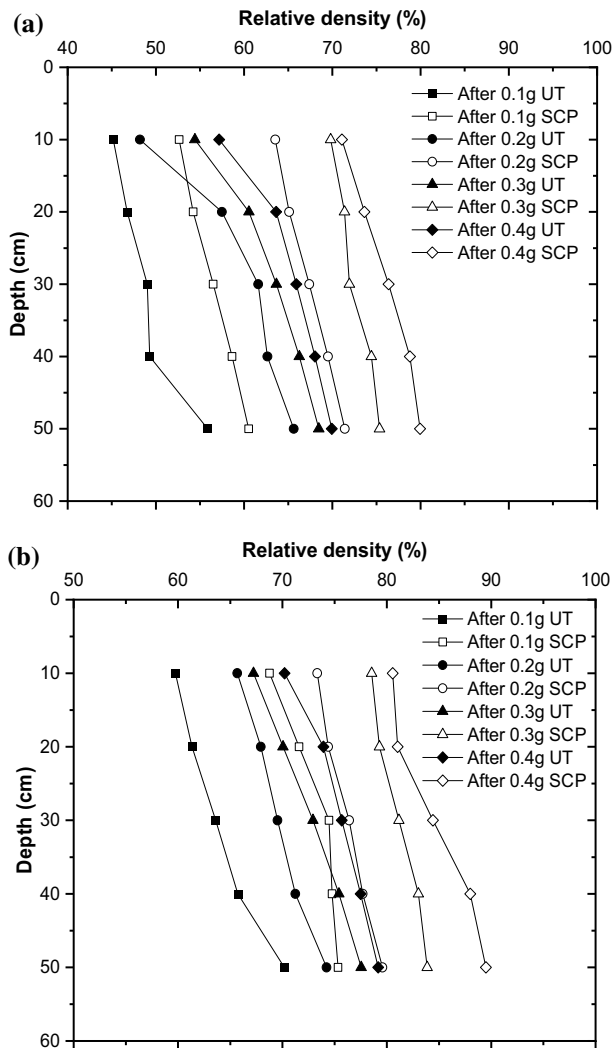
Fig. 4 Cone penetration resistance variations for SCP treated and untreated (UT) soil conditions **a** 40% relative density; **b** 60% relative density



4.1.2 Effect of improvement in in-situ soil density due to Sand compaction pile system under repeated loading

The effect of repeated acceleration loading on saturated ground deposit is discussed in this section. The application of repeated incremental acceleration loading is performed to the both unreinforced and reinforced ground only after complete dissipation of generated pore water pressure from previous loading. Also, penetration tests were carried out on both unreinforced and reinforced ground after each loading and corresponding penetration resistance and density was estimated. Figure 4 a shows the obtained penetration resistance, under repeated loading for both treated and untreated ground prepared with 40% and 60% density. The continuous application of acceleration loading induces reorientation of sand particles and causing soil densification after each loading. However, the continuous change in soil fabric and uneven soil deposition resulted in non-uniform densification with depth. This

Fig. 5 Relative density variations for SCP treated and untreated (UT) soil conditions **a** 40% relative density; **b** 60% relative density



was evident from both penetration resistance and relative density results shown in Figs. 4 and 5 for untreated and treated deposits. In case of treated ground, combined of installation effects of sand compaction pile system induces uniformity in density with depth. Further, the continuous occurrence of soil densification due to repeated loading resulted in higher penetration resistance than untreated ground. The continuous increment in density of the surrounding ground due to continuous shaking imparts effective confinement to the reinforcing column which further improves the seismic resistance of the ground. Overall, the initial improvement in density due to SCP installation i.e. 28% for 40% ground and 18% for 60% ground contributed in mitigating liquefaction at 0.1 g acceleration loading. The effect of soil densification induced by SCP system and unreinforced ground was further validated in terms of pore pressure response and discussed in the following section. Densification mechanism induced by SCP system was critical in controlling the generation of EPWP. Compared to untreated sand deposits, improvement percentage in soil density was reported as 17% and 15% after the installation of SCP's, and 15% and 13% improved was observed at the end of final shaking event for 40% and 60% dense ground conditions respectively. Selection of improvement ratio and pattern of installation are critical in the improvement of sand density reinforced with sand compaction piles. Reorientation of soil particles and soil consolidation are mainly responsible for improvement in sand density under the application of repeated shaking events.

4.1.3 Void ratio variation for treated and untreated ground conditions

Significance of void ratio in liquefaction potential is another influencing parameter to assess the efficacy of any ground improvement technique. As discussed, the reorientation of sand particles and change in soil fabric structure due to repeated shaking events resulted in redistribution of void ratio for untreated and treated ground. The void ratio variation with depth was estimated using Eq. 3.

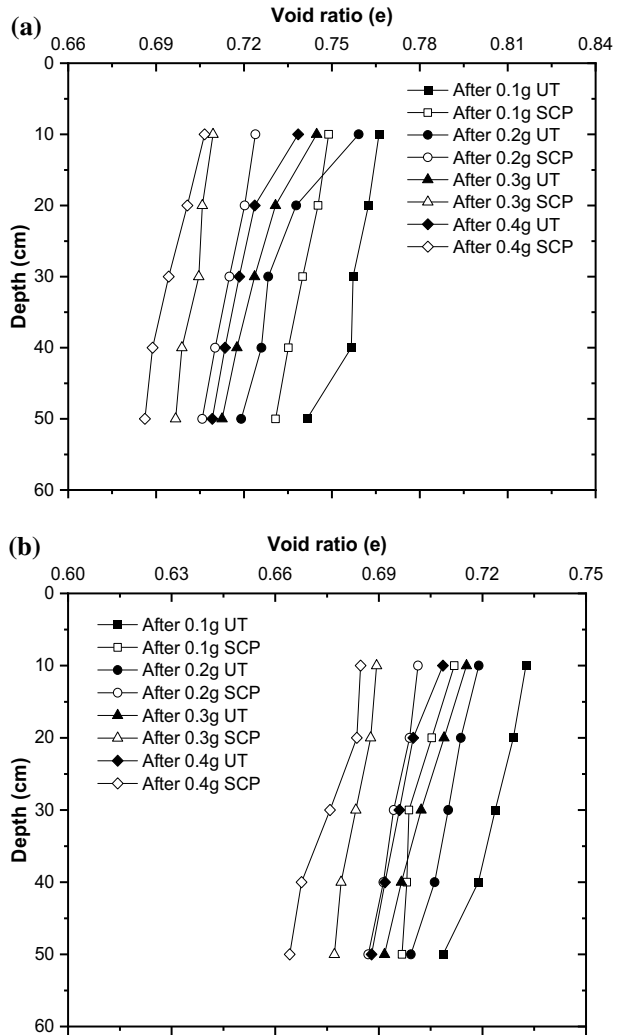
$$e = e_{\max} - D_R(e_{\max} - e_{\min}) \quad (3)$$

Where e and D_R are void ratio and relative density of the sand at that particular depth and e_{\max} and e_{\min} are the maximum and minimum void ratio as shown in Table 1. The variation in void ratio with depth for repeated acceleration loading is shown in Fig. 6. The reduction in void ratio was about 1.5% to 6% and 1.2% to 4.5% in case of treated ground compared to untreated for 40% and 60% density. The reduction in void ratio validated the occurrence of improvement in density due to acceleration loading. The reduction percentage was found higher for 40% ground than 60% ground as expected. Further, the reduction in void ratio due to density improvement induced by the SCP system additionally highlights the beneficial effect of reinforcement system in mitigating generation of pore water pressures especially during repeated shaking events.

4.2 Influence of pore water pressure response on reliquefaction resistance

Generally, the occurrence of liquefaction and reliquefaction in saturated sand deposits was assessed through generated pore water pressure and estimated pore pressure ratio. In this study, two glass tube piezometers were used for monitoring pore pressure response at 0.2 m and 0.4 m depth within the prepared ground. Figures 7 and 8 shows the obtained time history of EPWP at different depths for 40% and 60% density ground with and without SCP system at repeated incremental acceleration loading conditions i.e. 0.1 g, 0.2 g,

Fig. 6 Void ratio variations with respect to depth for SCP treated and untreated (UT) soil conditions **a** 40% relative density; **b** 60% relative density



0.3 g and 0.4 g at 5 Hz frequency with 40 s shaking duration. During experimental testing, application of sequential acceleration loading to the ground was carried only after dissipation of generated pore water pressure from previous loading which can be estimated from the installed glass piezometers inside the ground.

In case of untreated ground, generation of EPWP was observed maximum for 40% density ground than 60% density as expected. However, due to repeated acceleration loading conditions; increment in density with depth was observed for both the ground conditions. The increment in density was evaluated using cone penetrometer equipment. Further with the increase in the density of the ground i.e. 60%, the increment in density with depth under repeated shaking also increases. In case of untreated ground conditions, the increment in density under repeated shaking conditions was 58% to 68% for 40% ground and 18% to 30% for 60% ground respectively and found linearly increases

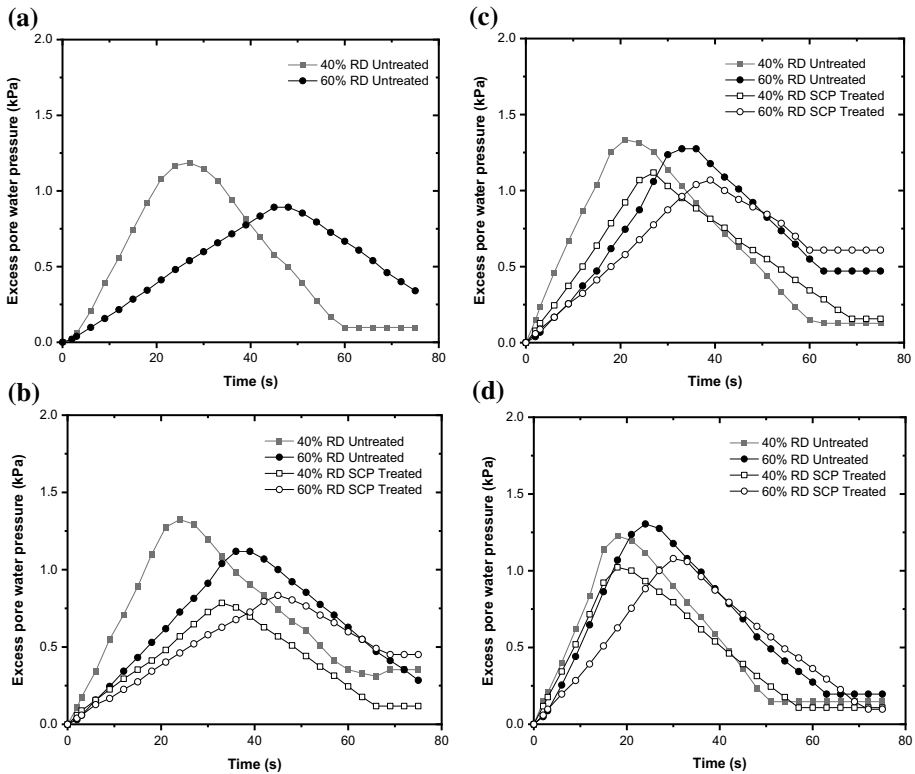


Fig. 7 Time history of EPWP for treated and untreated soil conditions at top piezometer **a** 0.1 g; **b** 0.2 g; **c** 0.3 g; **d** 0.4 g

with depth. The generation of pore water pressures under repeated shaking events suggesting that, improvement in density was not uniform with depth resulting in generation of pore water pressures from bottom to top and made soil at shallow depth more susceptible to liquefaction and reliquefaction. This was found evident from the time of liquefaction occurrence under repeated shaking events. The liquefaction time can be assessed in terms of build-up time (t_1), duration (t_2) and dissipation of excess pore water pressures (t_3). The obtained results were tabulated in Table 2. In case of untreated saturated ground, (t_1) decreases with the increase in applied acceleration loading. Though density plays a major role improving seismic response of saturated ground, occurrence of non-uniformity in density induces generation of pore water pressures and make soil more susceptible to reliquefaction in case of repeated shaking events.

When SCP treated ground subjected to repeated shaking events, generation of pore water pressures were found minimum compared to untreated ground. The same can be verified from Figs. 7 and 8 respectively. During lower to medium acceleration loading conditions (i.e. 0.1 g and 0.2 g) generation of pore water pressures was not observed at 0.1 g loading and limited pore pressure was generated at 0.2 g shaking for both 40% and 60% ground conditions. The initial improvement in density due to SCP installation improves seismic resistance during low to medium acceleration loading. This can be verified by the obtained improvement in density values obtained after SCP installation and density results

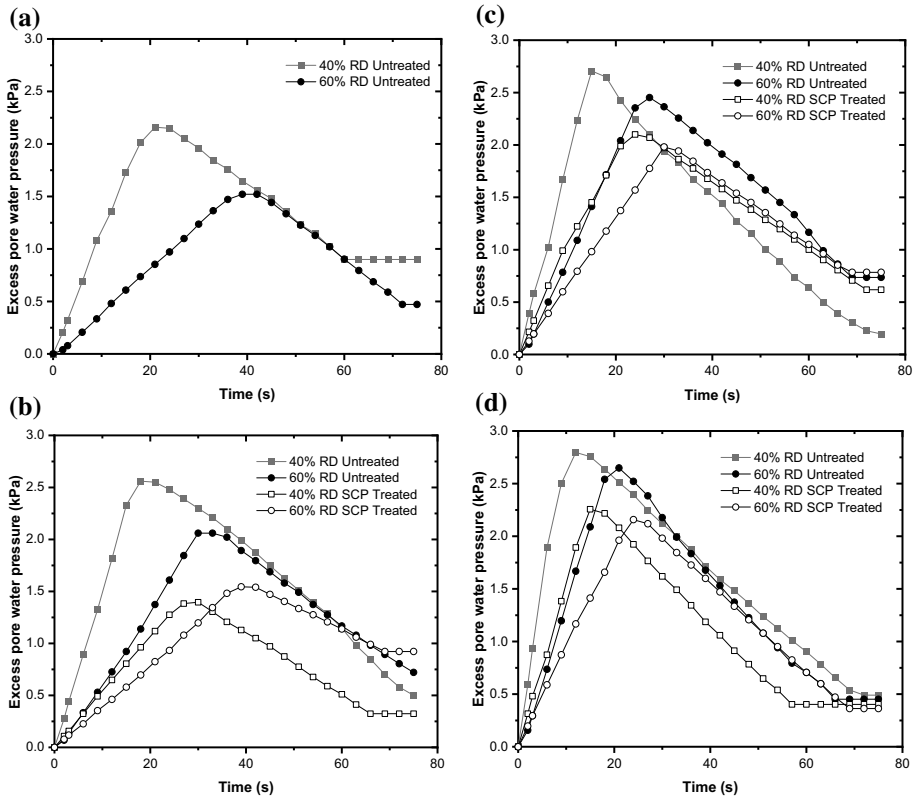


Fig. 8 Time history of EPWP for treated and untreated soil conditions at bottom piezometer **a** 0.1 g; **b** 0.2 g; **c** 0.3 g; **d** 0.4 g

Table 2 Effect of SCP on t_1 , t_2 , and t_3

Density considered	Input motion (g)	Maximum pore water pressure built-up time t_1 (s)				Maximum pore water pressure duration time t_2 (s)				Maximum pore water pressure dissipation time t_3 (s)			
		Untreated		SCP		Untreated		SCP		Untreated		SCP	
		B	T	B	T	B	T	B	T	B	T	B	T
40%	0.10	20	25	0	0	3	3	0	0	71	60	0	0
	0.20	17	22	28	33	4	3	4	3	80	70	66	69
	0.30	14	19	21	25	2	2	3	3	74	61	70	72
	0.40	11	16	14	17	2	3	4	3	71	51	63	60
60%	0.10	38	45	0	0	6	5	0	0	73	73	0	0
	0.20	31	38	38	44	6	5	4	3	76	76	70	69
	0.30	25	31	30	37	5	6	3	3	75	63	68	63
	0.40	19	24	23	30	4	4	4	3	75	68	72	73

after repeated loading events. Interestingly, in all the cases SCP treated ground showed uniformity in density with depth which improves the seismic resistance of saturated ground during dynamic loading. Occurrence of uniformity in ground conditions during initial loading mitigates generation of pore water pressures and during repeated acceleration loading, limited generation of pore water pressures were observed. The reduction in generated excess pore water pressure during repeated loading was found to be 16 to 40% at 0.4 m depth and 20% to 46% at 0.2 m depth for 40% relative density and 17% to 25% at 0.4 m depth and 18% to 25% at 0.2 m depth for 60% density ground. Further, the time of liquefaction increases for the SCP treated ground which verified the performance of the improvement system under repeated shaking events. Further, the reduction in generated pore water pressures at 40% ground condition (i.e. 40% to 46% for 0.4 m and 0.2 m depth respectively at the end of repeated loading) suggesting that, installation of SCP inside the ground limits occurrence of liquefaction and reliquefaction and stabilise the soil at shallow depth. The uniformity in soil densification due to SCP installation additionally improves the seismic resistance of the saturated ground deposit. Also, the continuous generation of pore water pressures during high to intense acceleration loading suggested the influence of area replacement ratio in improving the seismic performance of saturated ground deposits. The improvement ratio selected for the study i.e. 3% performs better during low to medium repeated acceleration loading conditions. However, during very high to intense loading; the selected area replacement ratio was not found adequate and suggested the need of proper area replacement ratio for further improving the seismic resistance of the ground.

The effect of pore pressure ratio estimated from the generated pore water pressure for treated and untreated ground is discussed in this section. It can be calculated using the formula

$$r_u = \frac{U}{\sigma'_{vo}} \quad (4)$$

where U is the excess pore water pressure (in kPa) and σ'_{vo} is the effective overburden pressure of the sand deposits calculated at that particular depth (in kPa).

The estimated pressure ratio for the treated and untreated ground for varying density under repeated shaking events is shown in Figs. 9 and 10. It was observed that, the estimated pore pressure ratio for the treated and untreated ground found to be increased, with the increase in acceleration loading under repeated shaking events. The generation of (r_u) is found higher at shallow depth i.e., 0.2 m (T) than at bottom 0.4 m depth (B) due to soil densification and overburden effects. Comparatively, the estimated pore pressure ratio for the treated deposits found lower than untreated ground. This was more pronounced in case of 40% ground. The observed reduction in maximum (r_u) was found to be 15% to 34% at Top (T) and 23% to 40% at Bottom (B) depth for 40% density and 26% to 36% and 26.5% to 36.5% at Top (T) and Bottom (B) depth respectively for 60% density ground. This verified the efficiency of SCP system in inducing soil densification mechanism in which contributed in mitigating generation of EPWP under repeated shaking events especially at loose ground conditions. Further, due to uniformity in ground density due to SCP installation induce uniform improvement in ground density during repeated shaking which further contribute in minimizing generation of pore water pressures. Due to this uniformity in densification, no liquefaction and reliquefaction was observed on the treated ground. In case of untreated ground, occurrence of non-uniformity in density with depth induces upward generation of pore water pressures from bottom to top and made soil at shallow depth more vulnerable to liquefaction and reliquefaction. The selected area replacement ratio for the

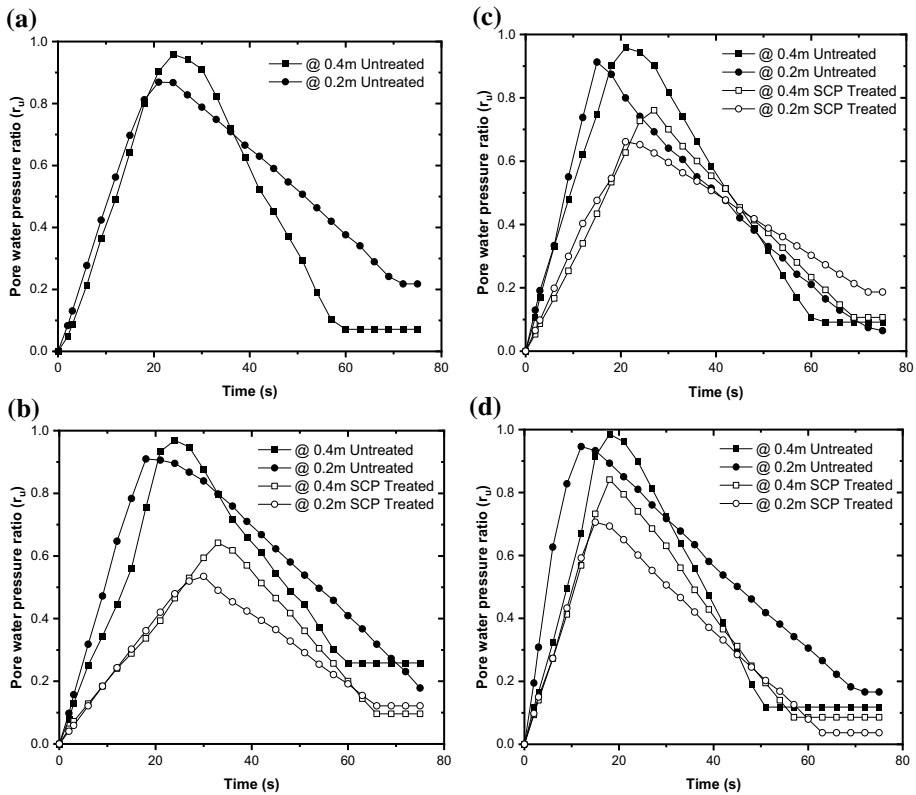


Fig. 9 Time history of Pore water pressure ratio for SCP treated and untreated soil conditions for 40% relative density **a** 0.1 g; **b** 0.2 g; **c** 0.3 g; **d** 0.4 g

SCP system mitigates generation of pore water pressure at 0.1 g loading and minimizes generation of pore water pressure during repeated shaking events. This improves the seismic response of the ground against liquefaction and reliquefaction.

4.3 Foundation settlement and soil subsidence

Occurrence of liquefaction and reliquefaction induce both foundation and soil located at shallow depth more susceptible to failures. Hence, in this study, the stability of shallow foundation resting on saturated ground under repeated dynamic loading was investigated. Using scaled foundation model, the observed foundation settlement and soil displacement was measured and compared. Using LVDT and settlement plates, both foundation settlement and soil displacement for the treated and untreated ground was measured and compared.

The obtained foundation settlement corresponding to 40% and 60% relative density subjected to repeated acceleration loading for both the treated and untreated ground is shown in Fig. 11. In both cases, the footing model was placed at the center of the prepared ground. The initial improvement induced by SCP system on 40% and 60% ground enhances the stability of the foundation and no foundation settlement was observed after 0.1 g acceleration

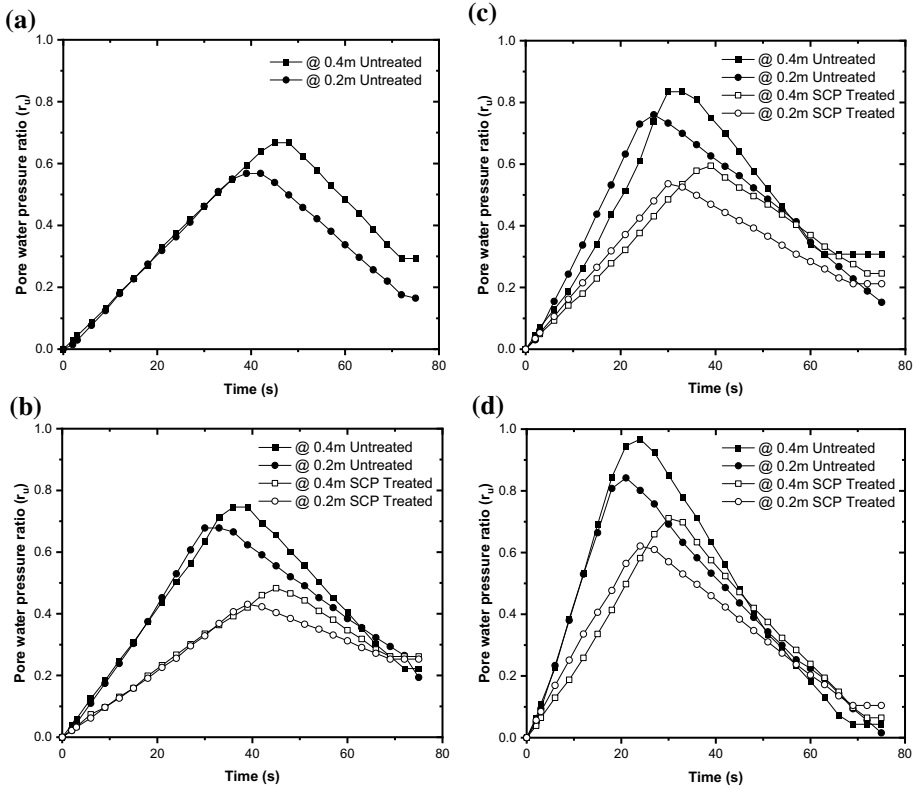
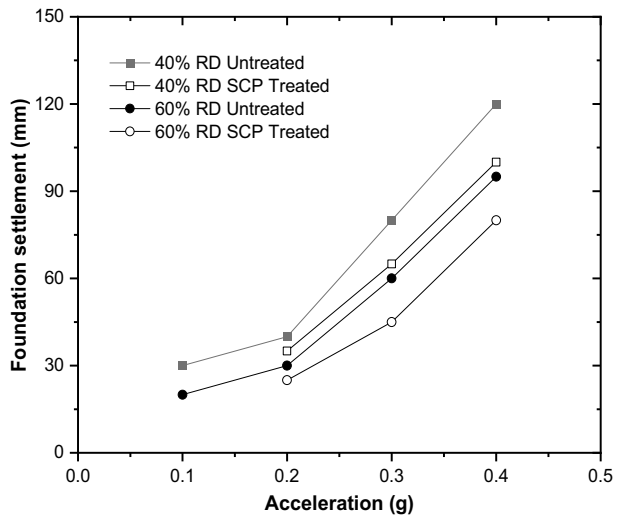


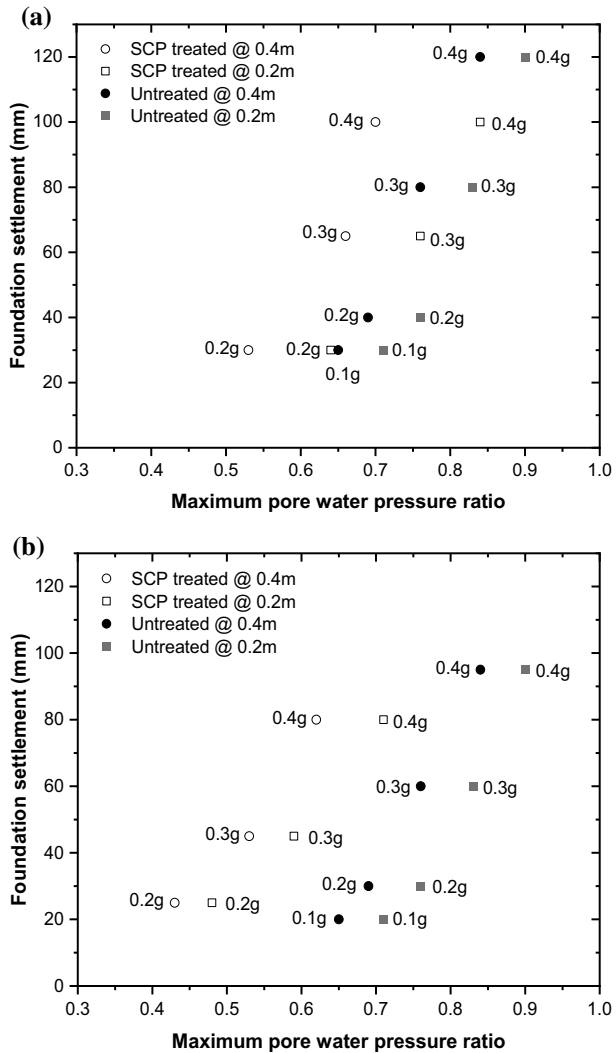
Fig. 10 Time history of Pore water pressure ratio for SCP treated and untreated soil conditions for 60% relative density **a** 0.1 g; **b** 0.2 g; **c** 0.3 g; **d** 0.4 g

Fig. 11 Foundation settlement at varying accelerations for 40% and 60% relative density (RD) for treated and untreated soil conditions



loading. As discussed in the previous section, improvement in density mitigates generation of pore water pressure thereby improving the seismic response of the ground at 0.1 g acceleration loading. However, under repeated shaking events and with the limited generation of pore water pressures, settlement of the footing was observed from 0.2 g to 0.4 g acceleration loading. The generation of pore water pressured mainly due to the application of longer duration of shaking which induces generation of pore water pressure from bottom to top. In case of treated ground, the uniformity in density with depth delays generation of pore water pressure and in case of untreated deposits, the non-uniformity with depth due to repeated shaking induces rapid generation of pore water pressures from bottom to top. This made soil at shallow depth more vulnerable and induces increment in foundation settlement. The reduction in foundation settlement for the treated ground found to be 25%, 19% and 17% for 40% and 17%, 16% and 15% for 60% density ground at 0.2 g, 0.3 g and 0.4 g respectively.

Fig. 12 Untreated and treated foundation settlement versus maximum pore water pressure ratio **a** 40% relative density; **b** 60% relative density



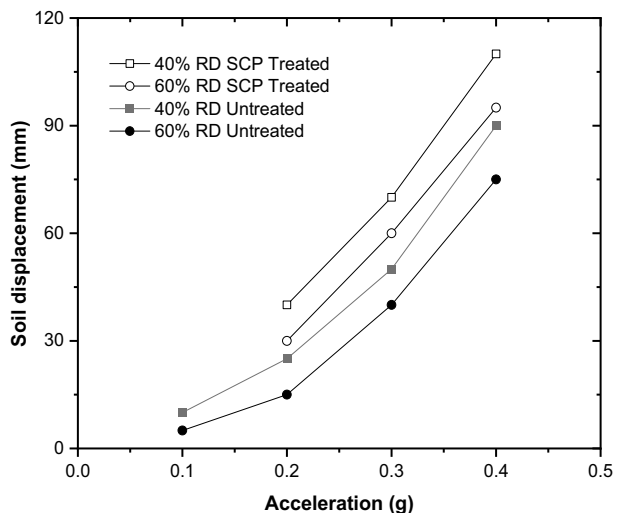
The performance of SCP system was further validated by comparing estimated pore water pressure ratio (r_u) and obtained foundation settlement under repeated shaking events. The estimated (r_u) based on the generated EPWP and corresponding foundation settlement was shown in Fig. 12. With the reduction in maximum (r_u) for untreated and treated ground i.e., 15% to 34% for 40% ground and 26% to 36% for 60% density ground at shallow depths (0.2 m), the reduction in foundation settlement was about 17% to 25% and 15% to 17% respectively. The reduction in maximum (r_u) at shallow depths verified the efficacy of treated sand deposits in mitigating generation of EPWP, foundation settlement reduction and improvement in seismic resistance of prepared ground against liquefaction and re-liquefaction. Thus, the soil densification mechanism induced by SCP system with 3% area replacement ratio found successful in mitigating reliquefaction phenomenon even during high intense shaking events (0.4 g) and with longer shaking duration (40 s).

The effect of selected ground improvement system was also assessed by estimating soil displacement using settlement plates. The measured soil subsidence under successive shaking events is shown in Fig. 13. Similar to foundation settlement, no soil displacement was observed at 0.1 g loading in treated ground. Also, the observed soil displacement increases for the treated ground which mainly due to densification effects of SCP system. The increase in soil displacement was about 15% to 40% for 40% dense ground and 27% to 50% for 60% dense ground respectively. The increment in soil displacement verified the occurrence of soil densification. From the density values, the improvement was further verified and found uniform with depth. Thus, SCP treated ground improves the seismic performance of the ground, minimizes foundation settlement and improves the stability of the ground even under repeated acceleration loading conditions.

4.4 Effect of CSR under repeated shaking events

Liquefaction potential and seismic demand of saturated sand deposits are generally evaluated in terms of Cyclic Stress Ratio (CSR) (Youd et al. 2001). To quantify the influence of densification mechanism induced by sand compaction pile improvement system; an attempt has been

Fig. 13 Surface soil displacement at varying accelerations for 40% and 60% relative density (RD) for treated and untreated soil conditions



made to evaluate CSR for the treated and untreated sand deposits subjected to repeated incremental shaking events. CSR was estimated using Eq. (5) proposed by Seed and Idriss (1971),

$$CSR = \left(\frac{\tau_{av}}{\sigma'_{vo}} \right) = 0.65 \times \left(\frac{a_{max}}{g} \right) \left(\frac{\sigma_{vo}}{\sigma'_{vo}} \right) r_d \tag{5}$$

a_{max} is maximum horizontal acceleration observed at the ground surface, g is acceleration of gravity, σ_{vo} and σ'_{vo} is the total and effective vertical overburden stress and r_d is stress reduction coefficient which decreases along the depth and calculated using Liao and Whitman (1986) recommendations as shown in Eq. (6)

$$r_d = 1.0 - 0.00765z \text{ For } z \leq 9.15\text{m} \tag{6}$$

z is the depth of ground surface in m.

Fig. 14 Untreated and treated cyclic stress ratio versus maximum pore water pressure ratio **a** 40% relative density; **b** 60% relative density

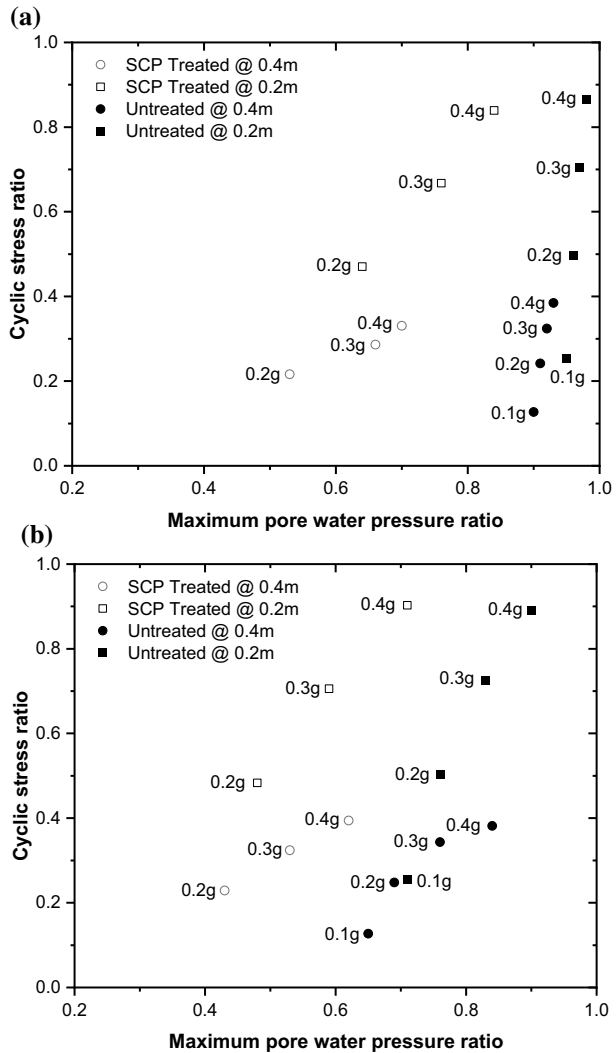
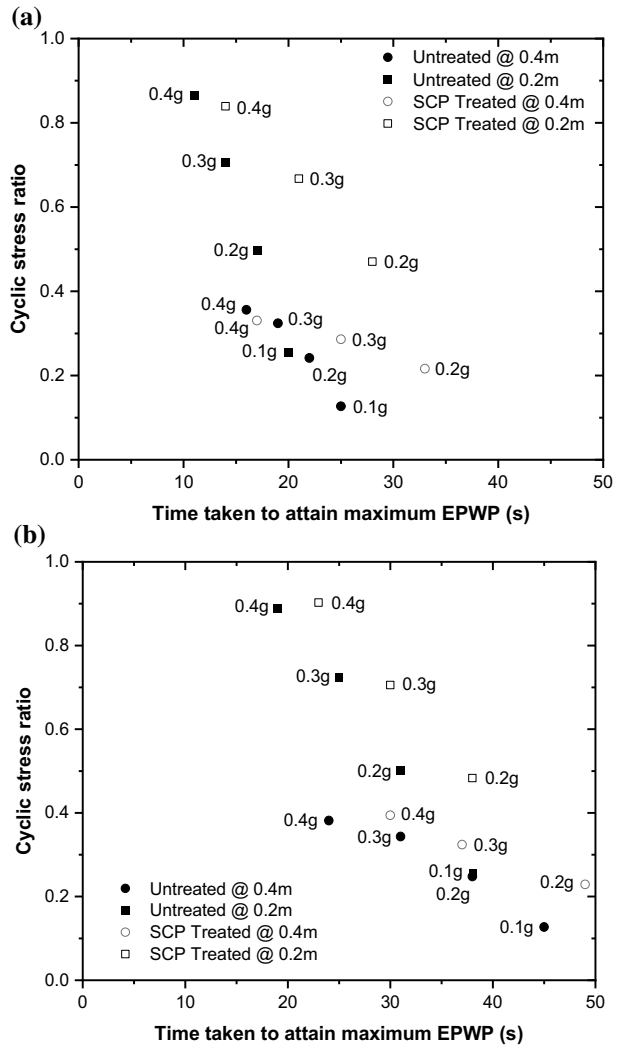


Fig. 15 Untreated and treated cyclic stress ratio versus time taken to attain maximum EPWP **a** 40% relative density; **b** 60% relative density



The estimated CSR values were compared with maximum pore water pressure ratio for treated and untreated sand deposits to verify the performance of SCP system. The obtained result is shown in Fig. 14 for 40% and 60% ground. Installation of SCP system delays generation of EPWP resulting in reduction in pore pressure ratio for both the ground conditions. Also, CSR found lesser due to improvement in density on the treated ground. This is also verified through Fig. 15. Interestingly, the reduction in CSR and pore pressure ratio was found more at shallow depths i.e. 0.2 m depth. The maximum reduction was about 12% for 40% ground and 8% for 60% density ground for 3% area replacement ratio of SCP system. This verified the performance of SCP improvement system against occurrence of liquefaction and reliquefaction when subjected to repeated shaking events. The reduction in CSR at 0.4 m depth was about 2% to 6% and 2% to 5% for 40% and 60% density and not much significant due to overburden effects. The

estimated CSR values, verified the need of selecting adequate area replacement system in improving the density of the ground. This will be helpful in mitigating generation of pore water pressures even at repeated shaking events. In this study, the SCP improvement system found effective in mitigating generation of pore water pressures, minimizing foundation settlement and improving seismic response of sand deposit especially at shallow depth. However, the generated pore water pressures under repeated loading highlighting the selection of proper area replacement ratio for improved performance.

5 Conclusions

The present study assessed the performance of SCP system in improving liquefaction and reliquefaction resistance of 40% and 60% saturated sand deposits under repeated incremental acceleration loading conditions. The investigations were carried using 1-g shaking table at 0.1 g, 0.2 g, 0.3 g, and 0.4 g sinusoidal acceleration loading conditions with 5 Hz frequency having 40 s shaking duration. For ground improvement four sand compaction piles installed in square pattern with the spacing of 450 mm through vibratory action with an improvement ratio 3% was chosen and installed. The performance of the ground with and without SCP system works was compared in terms of soil densification effects, generated pore water pressure and estimated pore pressure ratio, soil displacement and foundation settlement. Based on the obtained and estimated results, beneficial effects of SCP improvement system in mitigating liquefaction and reliquefaction were evaluated. The following conclusions were drawn from the experimental results and observations:

- (1). Installation of sand compaction pile group uniformly increases the relative density of saturated sand deposits. The improvement in soil densification due to SCP installation resists generation of pore water pressures and mitigates liquefaction during low to medium acceleration loading. The soil densification effects due to repeated loading further benefitted reduction in pore pressure generation about 41%, 18%, 14% in case of 40% dense ground and 21%, 17% and 15% for 60% ground conditions at 0.2 g, 0.3 g and 0.4 g acceleration loading at 0.2 m depth respectively. Thus the reduction in pore pressure generation indicates the improvement in soil resistance against liquefaction and reliquefaction at shallow depth.
- (2). In case of untreated ground, application of repeated incremental shaking events also induces soil densification effects. However, the redistributed soil grains after each loading were not uniform with depth causing continuous generation of pore water pressure despite of improvement in density. Thus, the generated pore water pressures from bottom to top made soil at shallow depth more susceptible to reliquefaction during subsequent shaking events.
- (3). The soil densification effect induced by SCP system improves the stability of foundation located at shallow depth even during repeated shaking events. Compared to untreated ground, SCP improved ground shows reduction in foundation settlement of about 17% to 25% for 40% ground and 15% to 17% for 60% ground under 0.2 g to 0.4 g repeated loading events with 3% improvement ratio of SCP system. Also, no foundation settlement was observed at 0.1 g acceleration loading for both 40% and 60% ground conditions due to density improvement effects. Thus, the SCP improvement system can be a viable improvement technique for improving seismic performance of saturated sand deposits even during repeated loading events. As discussed,

the stability of foundation can be further improved by selecting proper area replacement ratio of SCP system.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10518-021-01143-8>.

Acknowledgements The authors would like to thank the Director, CSIR-Central Building Research Institute, Roorkee, for giving permission to publish this research work. The authors would also like to thank the Head, Geotechnical Engineering Division, CSIR-CBRI for his continuous support during this research work.

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