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Confined Reinforcement Barrier system for Mitigating Generated Ground Motions in Liquefiable Soils

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Abstract. Earthquake often leads to liquefaction in loose saturated soils causing serious problem to the stability of infra-structures. Even though the excess pore pressure developed below the center of structure tends to be smaller, the developed accelerations also impact in inducing failure of structures. Stone column reinforcements have been extensively used for liquefaction induced ground motion mitigation in loose saturated soil deposits. In addition to stone columns, assessment studies using PU Foam (PUF) as isolation barrier also gaining importance for ground motion attenuation. However, use of PU foam material in liquefiable deposit is limited. In this study, an attempt has been made to develop a confined PUF barrier reinforcement system for mitigating the generated ground motions in liquefiable soils and their performance was compared with that of conventional stone column reinforcement. For experimental investigations saturated ground bed having 600 mm height was prepared with 40% relative density. Uniaxial shaking table tests were performed on saturated model ground with confined barrier reinforcement, conventional stone column reinforcement systems and compared with untreated ground under repeated earthquake loading conditions for efficiency assessment in terms of pore pressure ratio and ground motion attenuation. The results showed that the developed confined barrier reinforcement system performs well in mitigating the earthquake borne ground motions in liquefiable soils under repeated acceleration loading conditions as compared to conventional stone column reinforcement.

Keywords: Confined Barrier, Stone columns, Liquefiable soil, Ground motion, un-drained loading.

1 Introduction

Many catastrophic damages have been caused to the civil infra-structures due to soil liquefaction. Failure due to liquefaction is commonly observed in saturated cohesionless soil deposits. Additionally, when buildings are located near to epicenter, the effect of combined horizontal and vertical ground acceleration responses created vertical deformation and failure of structure [1]. Indicatively, in saturated soil deposits, as the generated excess pore water pressure increases, it reaches a unity where the soil surrounding the structure tends to flow as a liquid apparently leading to the failure of structure. Even if the excess pore pressure developed below the center of structure tends to be smaller than that away from the structure, the stability against combined horizontal and vertical acceleration should also be considered to ensure the safety of structures located in saturated ground deposits. Studies also show that the impact of generated ground motions are found to be higher in near fault regions, higher magnitude seismic events and in shorter period events relative to the horizontal component [2].

Stone columns (SC) have been extensively used as drainage member in saturated loose soil deposits which provide drainage and densification to the ground and mitigate the liquefaction effect and the associated ground deformations. However, the attenuation of incoming seismic vibrations in the saturated ground is least considered in stone column reinforcement. On the contrary, an alternative reinforcement system called confined isolation barrier reinforcement was used in this study to attenuate the ground motions generated during dynamic loading. The isolation barrier was made with commercially available PU foam which was widely accepted especially in shaking table tests as an absorbing boundary. The PUF confined barrier system when installed in liquefiable soil deposits found to effectively absorb both the incoming horizontal ground accelerations and the vertical uplift motion due to generation of excess pore pressure. The present research aims at comparing the sustainability of conventionally used stone column reinforcement system and PUF confined barrier reinforcement system in liquefiable soils when subjected to repeated earthquake events. The performance of barrier system was compared with conventional stone column reinforcement of 2.5% area ratio and tested under repeated acceleration loading conditions for liquefaction mitigation. Using, uniaxial shaking table experiments, the performance of prepared saturated model ground without reinforcement, with stone column reinforcement and with developed PUF confined barrier reinforcement systems are studied and presented.

2 Scope and Objective

The primary objective of this study is to compare the performance of the developed confined barrier reinforcement system that primarily uses energy absorption mechanism to absorb incoming ground motions and the conventionally adapted stone column reinforcement system that improve densification and drainage mechanism to stabilize the liquefiable ground when subjected to dynamic loading.

Stone columns are an array of crushed stone pillars. Reinforcement with Gravel drains stiffen and increase the bearing capacity of soil deposit thereby reducing liquefaction risk [3]. Considering their drainage and densification characteristics, they are employed in loose saturated ground deposits to increase the bearing capacity of soil as they offer easier dissipation of excess pore water pressure. However, the clogging effect of stone columns decreases their efficiency under multiple shaking events. The confined barrier reinforcement was prepared from Poly urethane material which is highly known for its shock absorbing capacity and damping properties. PU foam infill trenches had a good vibration isolation capacity and proved to be very effective in damping out ground-borne vibrations [4]. In order to prevent the intrusion of finer sand particles, geotextile was wrapped around the PUF barrier and then installed.

For experimental studies, poorly graded sand was selected to model liquefiable ground having 40% relative density. The developed confined barrier reinforcement and stone column reinforcement were installed in the prepared model ground and tested under sub-sequential sinusoidal acceleration loading conditions in order to evaluate their isolation performance when subjected to repeated action of soil-liquefaction effect.

3 Methodology

3.1 Soil selected for the study

Soil sample for experimental studies was collected from solani river bed in Roorkee, Uttarakhand. Laboratory experiments such as specific gravity, sieve analysis, relative density and permeability tests were carried out to determine the soil properties and the soil is classified as poorly graded sand (SP) as per Indian standard classification [IS 2720 Part 4 – 1985]. The gradation curve for the soil is shown in Fig. 1. It can be seen that, the gradation falls within the liquefaction susceptibility as proposed by Tsuchida H, 1970 [5]. For testing, model tank of dimension 1.4 m × 1 m × 1 m was used for ground preparation.

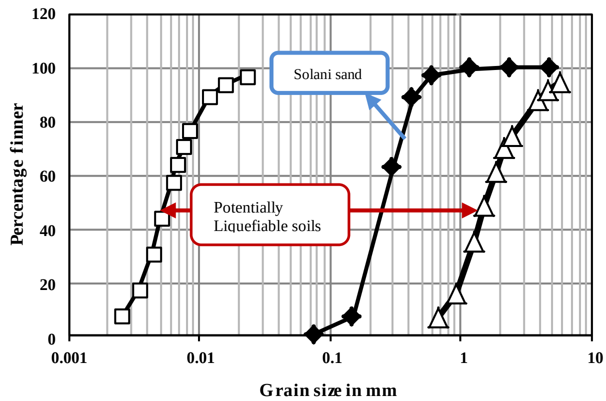

Fig. 1. Grain size distribution curve for Solani river sand

3.2 Preparation of un-reinforced model ground

The saturated ground model was prepared using wet sedimentation technique. The liquefaction response of soil highly depends on the method of sample preparation [6]. In wet sedimentation method, the desired relative density for soil is achieved by first adding the water required for complete saturation of soil initially followed by sand pouring inside the tank. The sand was poured through a conical hopper having 60° inverted cone at bottom from a calculated height which was estimated from the height of fall experiments. The height of pouring was calculated as 110 mm for achieving 40% relative density. For experimental testing, ground bed having 40% density was prepared and tested with and without soil reinforcement under repeated acceleration loading condition.

The saturated soil ground bed having 600mm height was prepared in three layers each of 200 mm height for achieving uniformity in sand bed preparation. For monitoring pore water pressure generated during shaking, two piezometers were fixed at a height of 200 mm and 400 mm from the bottom of the tank respectively. For estimating acceleration response, three accelerometers were placed at 100 mm, 300mm and 400 mm depth respectively from the top ground surface. For measuring foundation displacements, a scaled shallow footing model was embedded inside the prepared ground bed. Fig. 2 showing the sectional view of prepared model ground with accelerometer and piezometer connection details. Then, the prepared unreinforced ground bed was subjected to repeated acceleration loading. After completion of each test, the acceleration response and pore pressure variation was monitored and total foundation settlement was measured. Application of subsequent acceleration loading was carried out only after complete dissipation of generated pore water pressure from previous acceleration loading.

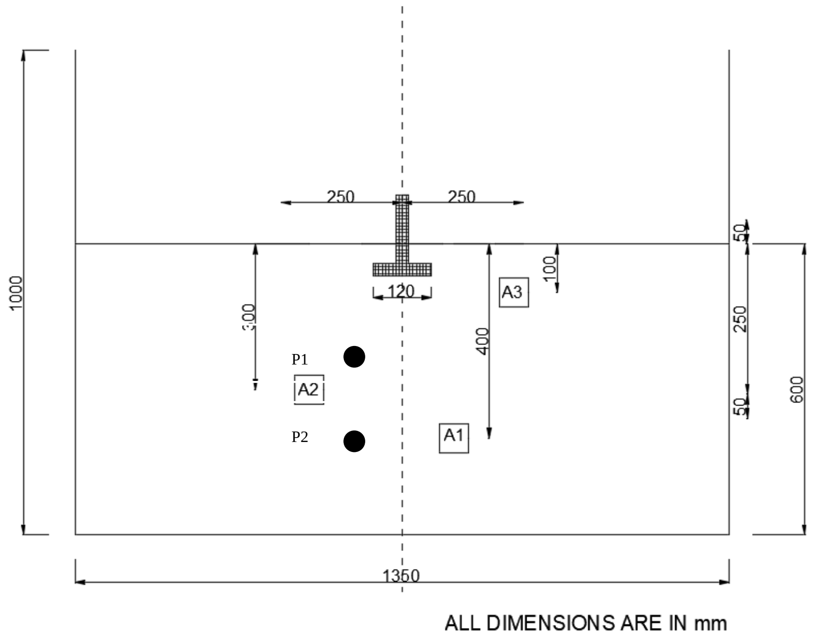

Fig. 2. Unreinforced model ground – Sectional view

3.3 Stone column reinforcement

The stone column reinforcement was designed for an area replacement ratio of 2.5%. The column network was designed in a square pattern with 4 stone columns surrounding the foundation area each having diameter (D) 110 mm and height 600mm. The center to center spacing of each column was calculated as 2.5D. Stone columns were installed in the ground model by displacement method [IS 15284 (Part1): 2003]. Coarse aggregates passing through 10mm and retaining on 4.5mm IS sieve was used for column construction.

For stone column construction, a casing pipe having outer diameter equivalent to diameter of stone column was driven to the entire depth of soil bed initially. The soil inside the casing was removed using an auger arrangement. Then, the stones were filled as layers of 150 mm depth each. After filling each layer, the stones were compacted 25 blows using hammer for achieving 76% equivalent to field density. After the installation of stone columns, scaled foundation model was embedded at center of the model ground to measure the settlement. For measuring acceleration response with drainage reinforcement, three accelerometers are placed inside the model tank i.e. A1 being at 400 mm depth, A2 at 100 mm depth and A3 being outside the barrier area at 100 mm depth from top ground surface respectively. Using two piezometers, the generated excess pore water pressure during acceleration loading was measured. The stone column reinforced model ground was then subjected to repeated acceleration loading. Fig. 3 showing the complete details of the prepared model ground reinforced with four stone columns in sectional view.

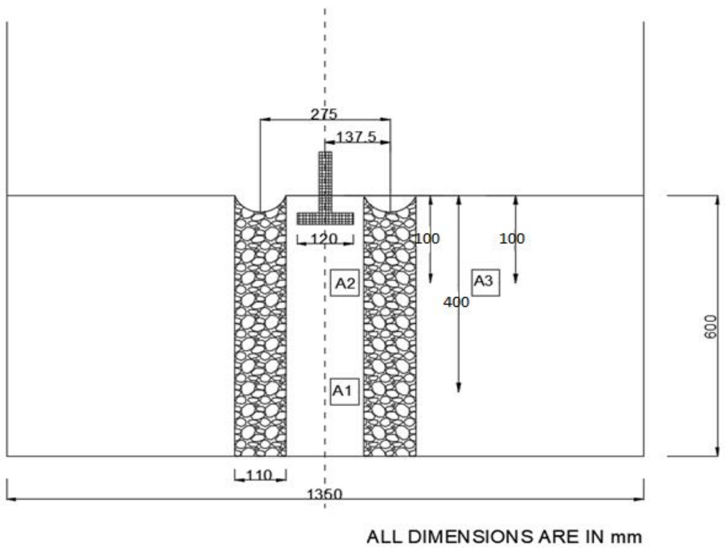

Fig. 3. Model ground reinforced with four stone columns – Sectional view

3.4 Confined barrier reinforcement

Poly urethane foam (PUF) was selected to design the confined isolation barrier considering its high resilience, abrasion resistance and vibration absorption characteristics. The liquid PU foam procured had a density of 1.1g/cc, damping ratio of about 0.08 and volume expansion factor of 30 times the original volume. The foam barrier was developed by mixing resin and hardener in a ratio of 1:1 inside the inverted T-shaped mold. To prevent soil intrusion during dynamic loading, the surface of the barrier system was covered with geotextile material. Since the application of acceleration loading in saturated soils can generate combined horizontal and vertical acceleration amplitudes, the confinement barrier model was developed similar to inverted T-shaped barrier system. This shape offers effective anchorage and also to absorb vertical ground accelerations generated due to shaking

Two inverted T-shaped anchored barrier models were prepared for the study with dimensions of Heel : 200 × 500 × 50 mm, Toe : 100 × 500 ×50 mm and Stem : 50 ×500 ×300 mm. The isolation barriers were placed to confine the foundation area by maintaining 500 mm c/c spacing between the stems. After achieving depth of 300 mm in ground preparation, the developed barrier model was placed over the ground and ground preparation was continued. Positioning of isolation barrier designed such that, the stem portion absorbs horizontal ground motions and heel-toe portions prevent the vertical uplift due to excess pore water pressure during dynamic loading. Fig. 4 showing the complete details of the PUF confined barrier reinforcement system installed inside the ground deposit. For measuring acceleration response, three accelerometers were placed inside the model ground, A1 and A2 being at 400mm and 100mm depth from top ground surface inside confinement whereas A3 being at 100mm depth from ground surface outside the confinement and two piezometers were used to measure the generated excess pore pressure. The reinforced model ground was then subjected to repeated acceleration loading and its acceleration response, pore pressure response and foundation settlement was observed and compared.

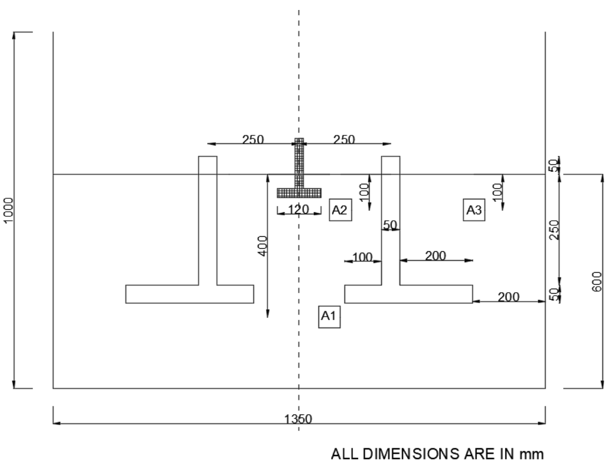

Fig. 4. PUF confined barrier reinforcement system – Sectional view

4 Experimental Testing Details

For experimental testing, repeated incremental sinusoidal acceleration loading having intensities 0.1g, 0.2g and 0.3g was applied to both unreinforced and reinforced model ground. The selected acceleration intensities tend to simulate the repetition of medium to severe earthquake conditions pertaining in the ground model [Resulting an intensity of VII to IX, as per Modified Mercalli Intensity Scale [7]. Also, the selection of repeated shaking is similar to observed repeated foreshock and main shock events observed during earthquake loading. Hence repeated incremental acceleration loading was selected and applied to the unreinforced and reinforced model ground. The effects of foundation settlement, acceleration response and pore pressure response in model ground with and without reinforcement systems are evaluated. The efficiencies of confined barrier reinforcement and stone column reinforcement under repeated occurrence of liquefaction effect in saturated model ground are compared.

5 Results and Discussion

5.1 Acceleration response

The obtained acceleration response of the prepared 40% density model ground under repeated sinusoidal acceleration loading condition with and without provision of reinforcements with respect to time are converted into frequency domain having 5 Hz base frequency by performing fast-fourier-transform. The resulting peak fourier amplitude reduction observed near the foundation model embedded in model ground with stone column reinforcement and confined barrier reinforcement are shown in Fig. 5 to evaluate their effectiveness in mitigation of liquefaction induced ground motion due to the provided repeated incremental acceleration loading.

It was evident from the figure that the peak fourier amplitude observed with stone column reinforcement condition had an average reduction of 69% and with PUF confined barrier reinforcement, an average reduction of about 85% was observed as compared to that of unreinforced model ground. This shows that the confined barrier reinforcement found to be more effective in controlling the generated ground motions and also efficient under repeated acceleration effect when compared to stone column reinforcement. This was mainly due to the damping characteristics of PU foam material which attenuates the incoming motions in to the structure.

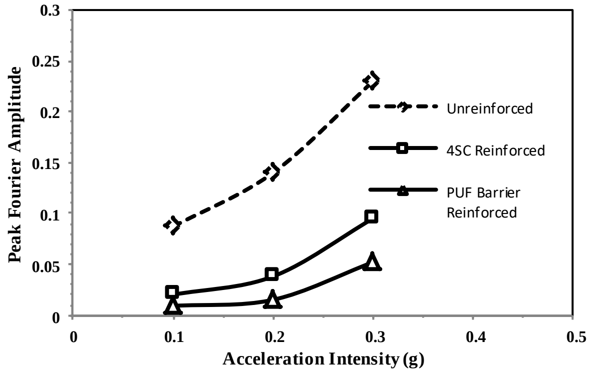

Fig. 5. Peak fourier amplitude reduction observed with stone column reinforcement and confined barrier reinforcement.

5.2 Amplitude Attenuation Ratio (A_R)

Amplitude attenuation ratio (A_R) is defined as the ratio of peak acceleration amplitude recorded with the provision of reinforcement to that without reinforcement under particular ground acceleration [8]. Fig. 6 showing the variation of amplitude attenuation curve under repeated acceleration loading conditions with stone column reinforcement and confined barrier reinforcement.

$$A_R = \frac{\text{Peak acceleration amplitude of ground with reinforcement}}{\text{Peak ground acceleration amplitude of ground without reinforcement}} \quad (1)$$

The variation pattern observed in both cases confirms the fact that liquefaction resistance of soil in consolidated state is less as compared to its virgin state [9]. It is also evident that the efficiency of reinforcement systems tends to decay under repeated undrained loading conditions. From the figure, it can be seen that the de-amplification capacity of PUF confined barrier reinforcement under repeated acceleration loading conditions is comparatively higher than stone column reinforcement.

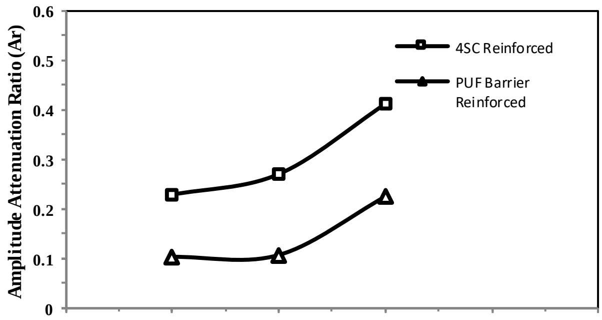

Fig. 6. Variation of Amplitude attenuation ratio curve observed under sub-sequential un-drained loading condition.

5.3 Effect of Pore water pressure ratio (r_u)

The pore water pressure ratio (r_u) is defined as ratio of excess pore water pressure U_{excess} to effective overburden pressure σ'_{vo}. The soil is considered to be liquefied when r_u value reaches unity. Due to the repeated un-drained shaking, the generation of pore water pressures from bottom to top makes soil at shallow depth more susceptible to liquefaction. Fig. 7 shows the estimated peak pore pressure ratio recorded in top piezometer under repeated acceleration loading with and without reinforcement.

$$r_u = \frac{U_{excess}}{\sigma'_{vo}} \tag{2}$$

From the figure, it is evident that the provision of reinforcement within the liquefiable deposit improves the seismic resistance by minimizing generation of pore water pressure. Comparatively, stone column improvement shows better performance than PU foam barrier system. It is also verified from the figure that, provision of PU foam barrier also performs better in minimizing generation of pore water pressure than untreated ground. The reduction in pore pressure ratio found to be 54%, 52% and 22% for PU foam treated ground and 84%, 79% and 73% for stone column treated ground under repeated loading condition. The enhanced reduction in pore pressure ratio in stone column treated ground may be due to the densification induced inside the ground bed during the stone column installation and due to drainage mechanism which dissipates the pore water pressure generation more effectively.

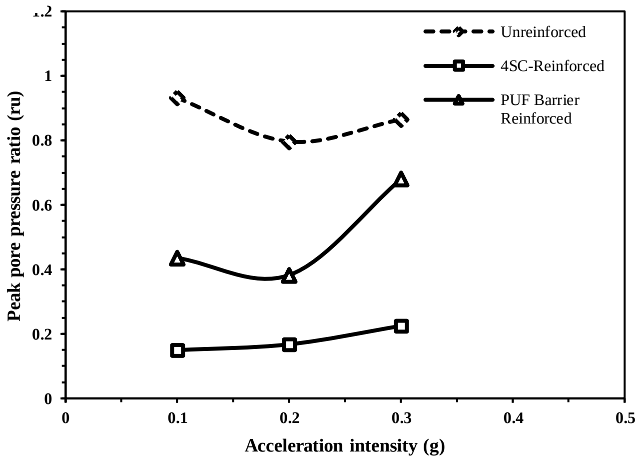

Fig. 7. Variation of peak pore pressure ratio observed under sub-sequential acceleration loading condition.

5.4 Foundation settlement

The foundation settlements during incremental sequential amplitude accelerations for both reinforced and unreinforced soil deposits are also evaluated and presented in Table 1.

It can be seen that the performance of stone column reinforcement was exceedingly well during initial accelerations. But, due to repeated shaking conditions, their efficiency gradually decreased due to clogging effect of stone columns. On the contrary, due to the enhanced absorption and confinement offered by PUF, the confined barrier was found more reliable during repeated loading conditions. At higher accelerations, slight deformation was observed in barrier due to continuous generation of pore water pressures. However, in both the treated conditions, installation of reinforcement member reduces foundation settlement in average by about 45% in case of PU foam treated ground and by about 48% for stone column treated ground.

Table 1. Foundation settlement of ground model under sub-sequential acceleration loading

Acceleration Intensity(g)	Foundation Settlement (cm)			%Reduction with 4-SC reinforcement	%Reduction with PUF-Barrier reinforcement
	Unreinforced	4 Stone Column-Reinforced	PUF confined barrier Reinforced		
0.1	4.2	2.2	3.2	47.62	23.81
0.2	9.8	4.9	4.6	50.00	53.06
0.3	14.4	7.8	6.1	45.83	57.64

6 Conclusions

Based on the conducted shaking table experiments and obtained results, following conclusions were made

1. The confined barrier reinforcement performs well in mitigating incoming ground motions to the structures through its absorption and damping characteristics even under repeated acceleration loading conditions. However, in the absence of drainage characteristics, the performance reduces at high acceleration loading conditions.
2. Provision of stone column reinforcement improves soil densification and drainage characteristics in liquefiable deposits. However, under repeated acceleration loading possibility of clogging due to intrusion of finer particles reduces its efficiency against liquefaction mitigation
3. Selection of proper ground improvement technique plays a major role in improving the seismic response of liquefiable deposit. Improvement in densification can improve seismic resistance but under repeated loading conditions, provision of drainage also contributes in improving resistance against liquefaction.

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