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Performance of Stone Column Subjected to Dynamic Loading in Sand Bed

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Abstract. The objective of this paper is to study the effect of dynamic loading on machine foundation and to compare the settlements of machine foundation with different types of stone columns. The Shaking table test is used throughout the study to investigate the effect of dynamic loading on machine foundation on soil bed with respective stone columns i.e., ordinary stone columns (OSC), encased stone columns (ESC), and reinforced stone columns (RSC) using a series of laboratory-scale model tests. Furthermore, the effect of various parameters such as length and diameter of stone column, amplitude of vibrations on the settlement of machine foundation supported on soil bed are with an OSC, ESC, and RSC are compared. From the result, it is evident that Encased Stone Columns are more effective as compared to ordinary stone column and reinforced stone column, towards reducing the settlement of footing subjected to dynamic loading.

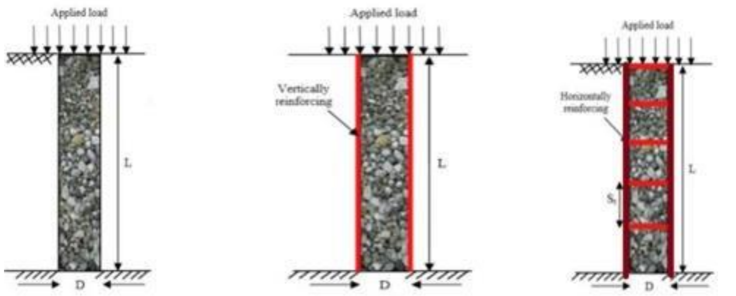
Keywords: Stone Column, Machine Foundation, Shaking Table, Dynamic Loading, Settlement, Soil Stabilization.

1 Introduction

Stone columns are densified granular material columns inserted in fine-grained material to transfer load down to the bearing strata or to strengthen the soil to improve liquefaction resistance. Stone columns are frequently used to improve the engineering characteristics of soft soils in order to sustain weakly and moderately loaded structures such as highway embankments and large diameter storage tanks.

A modern improvement in the stone column technique is reinforcing the column with horizontal layers of reinforcement or encasing the individual stone column with geosynthetics over the full or partial height of the column. The geosynthetics encasement multiplies the load-bearing capability of stone columns. To improve load carrying capacity and reduce stone column settlement, the granular bed can be combined with more reinforced geogrid. Ordinary Stone Column (OSC), Geosynthetic Encased Stone

Column (GESC), and Horizontal Encased Stone Column + Vertical Encased Stone Column (HESC + VESC) are the three types of stone columns shown in Figure 1.



(OSC) (GESC) (HESC + VESC)

Fig. 1. Different configurations of stone column.

Stone columns were installed using vibratory floats mounted on hydraulic excavators. The float is inserted into the ground to the desired depth using water and air jets. The void formed at the design depth is filled with granular material. This can be done with a bottom feed method or top feed method. Areas of applications of stone columns are infrastructure, mining, construction and liquefaction mitigation.

2 Literature Review

A brief review of literature on experimental studies on stone column is presented as follows.

Salemet.al (2017)[1] presented the findings of a study on the efficiency of stone columns as liquefaction remediation. The research was based on twenty-four case studies in which SPT and CPT tests were done before and after stone column strengthening. The mechanisms of densification and stiffening were studied, as well as their individual and combined impacts.

Kolekar et al. (2011)[2] conducted laboratory experiments to better understand how stone columns erected in marine clay behave when subjected to cyclic pressures. For single stone column testing, the unit cell method was used. To make a slurry, water equal to 1.5 times the clay's liquid limit was mixed with marine clay. The clay bed was consolidated from slurry under a pre-consolidation pressure of 18 kPa, which was determined through laboratory oedometer measurements, and the clay bed thickness after consolidation was 500 mm. A replacement approach was used to install a stone column with a diameter of 100 mm in the clay bed's center. Stone columns were made with aggregates ranging in size from 2 mm to 8 mm. The behavior of a stone column was investigated using both static and cyclic load tests. A total of four tests were performed: two static and two cyclic. One static load test was performed on an unreinforced clay bed, while the other was performed on a stone column reinforced clay bed. Only the reinforced clay bed was subjected to cyclic loading. In the case of static load testing, straincontrolled loading was used at a rate of 1.2 mm/min. One test was conducted in two stages for the cycle test on reinforced clay beds. Stage 1 consisted of a sinusoidal cyclic load equal to 35% of the static failure load of a reinforced stone column, followed by a sinusoidal cyclic load with a frequency of 0.1 Hz and 500 cycles. After 500 cycles, the same specimen was subjected to a static failure load of a reinforced stone column, followed by cyclic loading at the same frequency of 0.1 Hz, dubbed stage 2.

During and after seismic excitations, Cengiz et al. (2018)[3] conducted experimental tests on the behavior of Geosynthetic encased stone columns (GECs) and ordinary (conventional) stone columns (OSCs). Well-instrumented GECs and OSCs were installed in kaolinite clay beds that were consolidated in a big steel tank for this purpose. Surcharge loads were used to model the seismic behavior of columns supporting an embankment, and the experimental equipment was put through large-scale shaking table testing. The clay bed was made from kaolinite clay, which has a specific gravity (Gs) of 2.62 and plastic and liquid limits of 26% and 49%, respectively. The clay slurry was made with a water content of 75%, which was nearly 1.5 times the material's liquid limit. The GECs were encased in three different geotextiles. The first geotextile was TencatePolyfelt TS 10, a spun-bonded non-woven geotextile that was commercially accessible (designated as GT1). Sefitec PP 50 and Stabilenka 100 were the second and third geotextiles, respectively (designated as GT2 and GT3, respectively). These samples were tensile strength tested on 200 mm broad samples in line with DIN EN ISO 10319.

In their experimental tests, Adalier et al. (2003)[4] conducted centrifuge testing to evaluate the performance as a liquefaction countermeasure. Rather than the drainage impacts, the total site stiffening effects due to the stone column placement were evaluated. The behaviour of a saturated silt layer was studied under baseline conditions. Circumstances of dynamic excitation. That stratum was evaluated in a series of four independent model experiments, first without stone columns, then with stone columns in a free-field setting, and finally with a surface foundation surcharge. Based on the recorded dynamic responses, the underlying mechanism and effectiveness of the stone columns were discussed. We examined and reanalyzed the effect of the installed columns on excess pore pressures and deformations.

Nima Mehrannia et al (2018)[5] conducted experimental studies on soil improvement with stone columns and granular blankets. The bearing capacity of stone columns, granular blanket, and a combination of both methods in reinforced and unreinforced modes were studied using scaled physical models.

3 Experimental Investigations

1-g shaking table tests were carried out on Performance of Stone Column in Sand Bed Subjected to Dynamic Loading using acrylic tank of 0.6 m x 0.4 m x 0.6 m and the frequency of 2Hz for the amplitude of ±2mm and ±3mm respectively. Total four different series of shaking table tests were conducted: Series A: Test on sand bed without stone columns Series B: Test on sand bed with OSC Series C: Test on sand bed with ESC Series D: Test on sand bed with RSC

3.1 Materials used for Experimental Investigations

Soil.

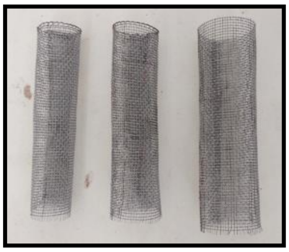
For the experimental investigation, Kanhan sand (cohesionless, dry and clean) available in Nagpur region of Vidarbha (MH) was used as the foundation soil. The test sand was angular and of uniform yellow color, with small proportion of black flint stones. The particle size of sand decided for the test was passing through 2 mm IS sieve.

Crushed Stone aggregate.

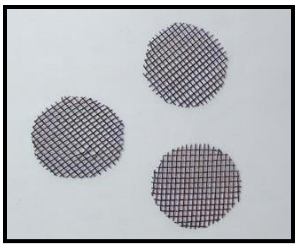
Crushed stone chips passing 6.3mm I.S sieve and retained on 2mm I.S sieve was used to form the stone column. The particle sizes for the column were as per the guidelines of Nayak (1983), which suggest that the particle size should be in the range of 1/6 to 1/7 diameter of the column (i.e.,30 mm, 36 mm & 45 mm respectively). The Specific gravity of crushed stone aggregates was (S.G) 2.75.

Steel wire mesh.

The reinforcements for horizontal and vertical encasing of stone column formed using a steel wire mesh had an aperture size 1mm × 1mm.



A)



B)

Fig. 2. Steel mesh used for A) Encasing B) Reinforcement of Stone Column.

The properties of sand, Crushed Stone aggregates and steel wire mesh are as shown in Table 1 below.

Table 1. Properties of sand, Crushed Stone aggregates and steel wire mesh

Sr. No.	Materials	Properties	Values
1	Sand	IS Classification	SP
		Specific Gravity	2.638
		Maximum Void Ratio ($e_{(max)}$)	0.79
		Minimum Void Ratio ($e_{(min)}$)	0.59

		Relative Density	36 %
		Angle of Internal Friction (ϕ)	34°
		Coefficient of Uniformity (C_u)	2.22
		Coefficient of Curvature (C_c)	1.4
2	Crushed Stone Aggregates	Specific Gravity	2.75
3	Steel Wire Mesh	Aperture Size (mm)	1×1

4 Experimental Set-up

The experimental set-up consists of shaking table, acrylic tank, data logger, control panel, accelerometer, LVDT and motor. The 3D view of experimental set-up is shown in Figure 3.

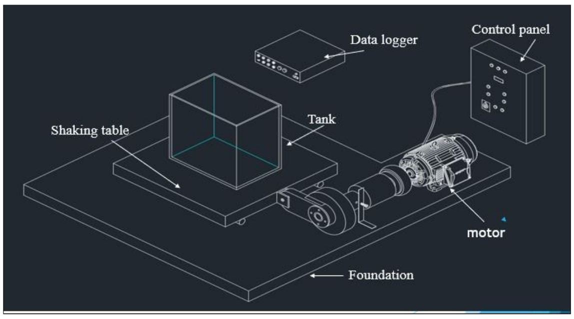


Fig. 3. 3D view of shaking table

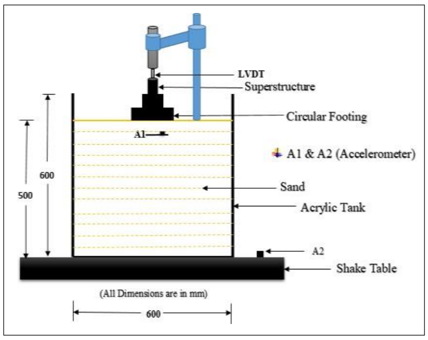
5 Experimental Test Procedure

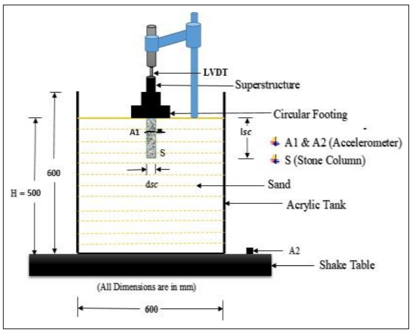
Using the gravity raining technique, the sand was filled with a relative density (Dr) of 36%, with a height of fall of 10cm up to the height of H. (Total height of sand bed). The sand bed was prepared to a depth of 1/3rd the height from the top of the respective stone column, and accelerometer 1 (i.e., A1) was placed at that level. After that, the remaining sand bed was prepared up to height H. After filling the tank, a plane wooden plate and a spirit level were used to level the bed's surface. The model footing, which was attached to the superstructure, was then placed in the center of the sand bed. The LVDT was mounted on the top surface of the superstructure to measure upward settlement as shown in Figure 4 (a). The Accelerometer 2 (i.e., A2) was fixed on the base of the shake table to measure acceleration coming to the shake table.

The displacement method was used to build the stone columns. For various experiments, the stone column diameters (dsc) were 30mm, 36mm, and 45mm. The stone column's length to diameter ratio (lsc/dsc) was kept at 5.0. The sand was filled up to the lowest level of the stone column, and a PVC pipe with a diameter equal to the stone column's diameter was installed in the center of the bed at that level. The sand bed preparation was completed up to the 2/3rd height of the stone column, when accelerometer 1 (i.e., A1) was installed. The sand bed was then raised to the desired height, and PVC pipe of the required height for each stone column was installed. The quantity of stone aggregate required to build the stone column was premeasured and put into the casing pipe in three layers, each of (lsc)/3 mm thickness, when the tank was filled. After adding stone aggregates in each layer, it was compressed by using a tamping rod with a 20mm diameter and 1600 gm weight that was dropped freely from a height of 50 mm for ten strikes. After each layer of aggregate was placed, the casing pipe was slowly pushed up for a distance equivalent to the thickness of that layer. Using the same method, the next layer of aggregates was compacted until the complete length of the stone column was created. The stone column's upper surface was levelled. Then, in the center of the sand bed, a footing attached to the superstructure was built. The LVDT was fixed on the base of the shake table to measure downward settlement, and the Accelerometer 2 (i.e., A2) was mounted on the top surface of the superstructure to measure upward settlement. A stone column with a footing and a superstructure is represented schematically which is shown in Figure 4 (b).

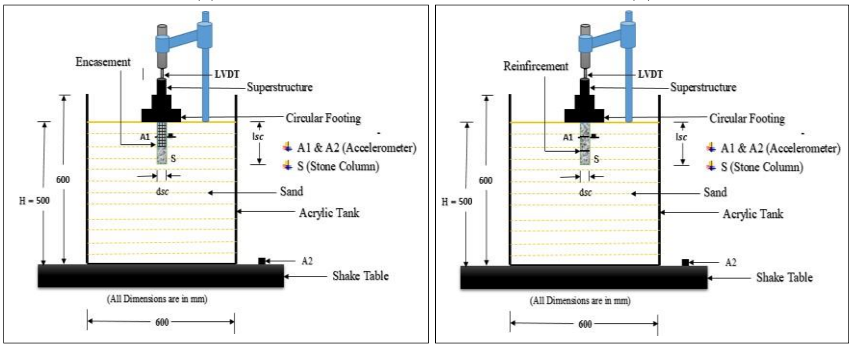
The placement of the encased Stone Column in the sand was identical to that of a regular stone column. While constructing the sand bed, steel wire mesh with a height of 100 mm from the top was joined to PVC pipe casing in a circular shape to provide encasement to the column. The schematic view of an incased stone column is shown in Figure 4 (c) (ESC). Crushed stone of a specific gradation was then poured in the same manner as a regular stone column. In all situations, the height of the encased chosen for experimental research was 100 mm, which was the "optimal height of encasement."

In the case of a reinforced stone column (RSC), the technique was similar to that of an ordinary stone column, with the exception that following compaction of one layer of stone column, a circular steel mesh was placed above that layer and on top of the prepared stone column. The schematic view of RSC is shown in Figure 4(d). The schematic perspective of the experimental test technique is shown in Figure 4 & Figure 5 shows the complete sequence of making ordinary stone column in sand bed.



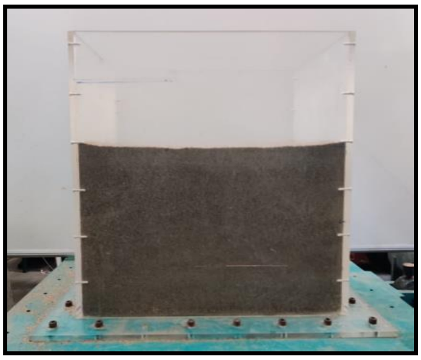


(a) (b)



(c) (d)

Fig. 4. Schematic view of experimental test procedure

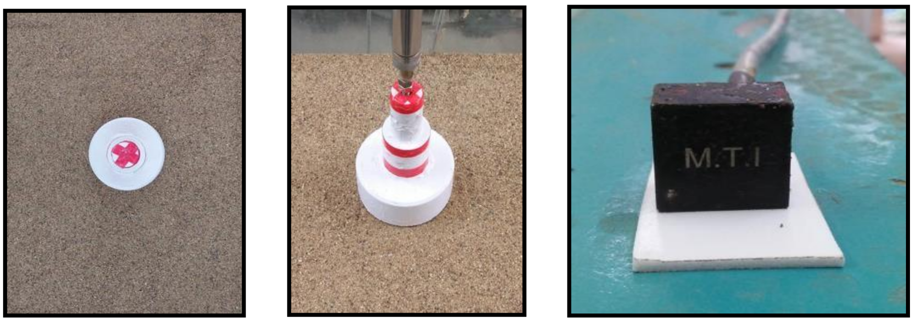


a)

b)

c)

d)



e) f) g)

Fig. 5. The complete sequence of making ordinary stone column in sand bed represented by :- a) Sand filled upto H – height of Respective stone column;b) Placement of Marked PVC pipe casing for stone column;c) Placement of accelerometer A1 on sand bed at 1/3 height of stone colum from top of sand; d) Top view of formed stone column; e) Top view of placement of footing and superstructure on stone column; f) Placement LVDT on superstructure;g) Accelerometer A2 mounted on base of shake table.

Results.

Experimental investigations were carried out on the loose sand bed with ordinary stone column, sand bed with encased stone column and sand bed with reinforced stone column subjected to dynamic loading with the constant natural frequency of machine foundation 2Hz, and amplitude of ± 2mm and ± 3mm. The results of all tests on the sand bed were compared in terms of the settlement and acceleration. Figure 5 shows typical settlement verses time graphs obtained from data logger.

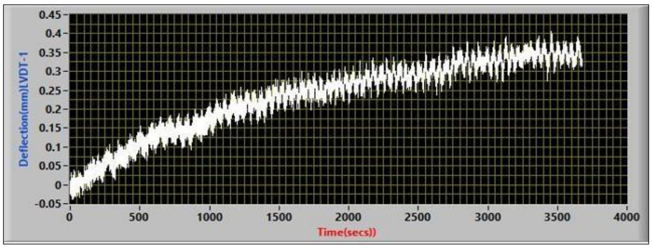


Fig. 5. Graph of Settlement verses Time (LVDT placed above Superstructure)

The settlement values of foundation on soil bed, soil bed provided with OSC, soil bed provided with RSC, and soil bed provided with encasement for ±2mm amplitude and ±3mm amplitude shown in following tables 2 and 3 respectively.

Table 2. Settlement values for dynamic loading with ± 2mm amplitude

Description	Diameter of stone column (cm)	Settlement (mm)
Sand Bed	-	0.36
	-	0.36
	-	0.36
Sand Bed with OSC	3	0.24
	3.6	0.19
	4.5	0.14
Sand Bed with RSC	3	0.127
	3.6	0.12
	4.5	0.112
Sand Bed with ESC	3	0.088
	3.6	0.067
	4.5	0.024

Table 3. Settlement values for dynamic loading with ± 3mm amplitude

Description	Diameter of stone column (cm)	Settlement (mm)
Sand Bed	-	0.43
	-	0.43
	-	0.43
Sand Bed with OSC	3	0.32
	3.6	0.22
	4.5	0.175
Sand Bed with RSC	3	0.142
	3.6	0.128
	4.5	0.117
Sand Bed with ESC	3	0.122
	3.6	0.113
	4.5	0.086

The performances of sand bed provided with OSC, ESC and RSC were analyzed in terms of percentage reduction in settlement of footing on sand bed without stone column. The effect of various parameters such as length and diameter of stone column, amplitude of vibrations on the settlement of footing were examined.

Table 4 and Figure 6 & Figure 7 show % reduction in settlement of footing on sand bed with OSC, RSC and ESC of different diameters and different amplitudes of vibrations, as compared with that of footing on sand bed without stone column.

Table 4. % Reduction in Settlement of foundation due to provision of OSC, ESC, and RSC

Amplitude of vibration (mm)	Diameter of stone column (cm)	% Reduction in settlement		
		Sand Bed with OSC	Sand Bed with RSC	Sand Bed with ESC
± 2 mm	3	50	186.46	309.09
	3.6	89.47	200	437.313
	4.5	157.14	221.42	1400
± 3 mm	3	34.37	202.81	252.45
	3.6	95.45	235.93	280.53
	4.5	145.71	267.52	400

The percentage reduction value of settlement for sand bed with OSC, sand bed with RSC and sand bed with ESC was more when it was compared with sand bed without stone column.

From the result, it is evident that Encased Stone Columns are more effective as compared to ordinary stone column and reinforced stone column, towards reducing the settlement of footing subjected to dynamic loading. The settlement was observed to be reduced up to 1400% by providing encased stone column.

Reinforced stone columns are, however, more effective than ordinary stone columns, towards reducing the settlement of footing subjected to dynamic loading. The settlement was observed to be reduced up to 250% by providing encased stone column.

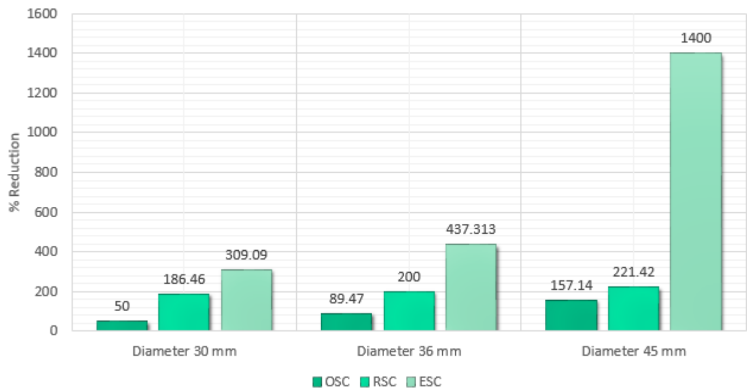


Fig. 6. % Reduction in settlement of foundation on soil provided with OSC, RSC and ESC for +2 mm amplitude

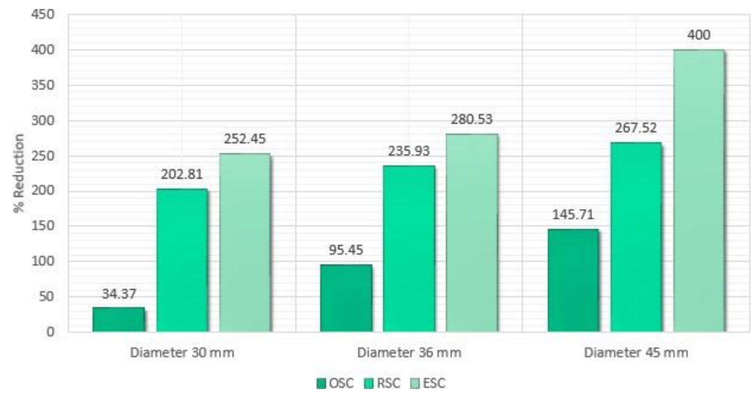


Fig. 7. % Reduction in settlement of foundation on soil provided with OSC, RSC and ESC for + 3 mm amplitude

6 Conclusions

Experimental investigations on footing supported on sand bed and provided with ordinary, encased and reinforced stone column and subjected to dynamic loading using shake table were performed and settlement of footing was determined in each case. Percentage reduction in settlement was determined to judge the performance of these systems.

Based on the experimental investigations on the behavior of model footing sand bed provided with ordinary stone column (OSC) / Encased stone column (ESC) / Reinforced stone column, following broad conclusions are drawn:

1. Encased stone column is more effective as compared to OSC & RSC.
2. Settlements of footing on sand bed provided with encased stone columns may be reduced up to 1400%.

3. Settlements of footing on sand bed provided with reinforced stone columns may be reduced up to 250%.

4. Settlements of footing on sand bed provided with ordinary stone columns may be reduced up to 150%.

5. The effect of providing stone column in soil bed and subjected to dynamic loading is more improved with increase in the diameter of stone column.

6. As the amplitude of vibration increases the performance of stone column in soil bed and subjected to dynamic loading is more enhanced.

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