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ORIGINAL PAPER

Stone Columns with Vertical Circumferential Nails: Laboratory Model Study

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Abstract This paper presents results from a series of laboratory plate load tests carried out in unit cell tanks to investigate the improvement in stiffness, load carrying capacity and resistance to bulging of stone columns installed in soft soils. A new method of reinforcing the stone columns with vertical nails installed along the circumference of the stone column is suggested for improving the performance of these columns. Tests were carried out with two types of loading (1) the entire area in the unit cell tank loaded, to estimate the stiffness of improved ground and (2) only the stone column loaded, to estimate the limiting axial capacity. It is found that stone columns reinforced with vertical nails along the circumference have much higher load carrying capacity and undergo lesser compression and lesser lateral bulging as compared to conventional stone columns. The benefit of vertical circumferential nails increases with increase in the diameter, number and depth of embedment of the nails. The improvement in the performance of stone column was found to be more significant, even with lower area ratio. It is found that reinforcing stone column with vertical circumferential nails at the top portion to a depth equal to three times the diameter of stone columns, will be adequate to prevent the column from excessive bulging and to improve its load carrying capacity substantially.

Keywords Stone columns · Vertical circumferential nails · Unit cell · Composite ground · Bulging · Ground improvement

1 Introduction

Due to the rapid growth of infrastructural facilities, there is a need to expand the construction activities also in areas with poor subsoil conditions, wherein the geotechnical engineers are challenged by the presence of various problematic soils with different engineering characteristics. Amongst the various techniques for improving in situ ground conditions, reinforcing the ground with stone columns or granular piles is one of the most versatile and cost effective technique. Stone columns provide the primary functions of reinforcement and drainage by improving the strength and deformation properties of the soft soil (Madhav and Miura 1994). They increase the unit weight of soil, drain rapidly the excess pore pressures generated and act as strong and stiff

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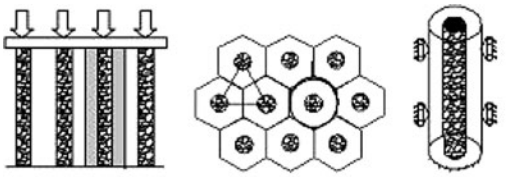
elements and carry higher shear stresses. They are installed in a wide variety of soils, ranging from loose sands to soft compressible clays. Stone columns have been and are being used in many difficult foundation sites throughout the world to increase the bearing capacity, to reduce the total and differential settlements, to increase the rate of consolidation, to improve slope stability of embankments and also to improve the resistance to liquefaction (Alamgir et al. 1996). Applications of stone columns include the support to embankments, liquid storage tanks, raft foundations and other low rise structures. Stone columns are most effective in clayey soils with undrained shear strength in the range of 7–50 kPa (Barksdale and Bachus 1983; IS:15284-2003).

It is well established that stone columns derive their load carrying capacity from the lateral confining pressure from the surrounding soils (Greenwood 1970; Hughes et al. 1975; Barksdale and Bachus 1983). When the stone columns are installed in very soft clays, they may not derive significant load carrying capacity, owing to the low lateral confinement offered by soft clays. McKenna et al. (1975) reported cases where the stone column was not restrained by the surrounding soft clay, which led to excessive bulging, and also the squeezing of soft clay into the voids of the aggregates. In order to enhance the performance of stone columns installed for treating weak deposits, it is imperative that the bulging tendency of the column should be restricted effectively. This could be possible if stone columns are encased with suitable geosynthetic (called as flexible skirt) or with a rigid pipe in top portion (called as rigid skirt) to impart the necessary confinement to improve their strength and stiffness. Alternatively, the stone columns are reinforced internally by stabilization of column material using concrete plugs, chemical grouting or by adding internal inclusions (geogrids, plastic fibers etc.), which will stiffen the column, and accordingly increase its bearing capacity. Several investigators have studied the strength and stiffness behavior of skirted/encased stone columns under vertical loading (Ranjan and Rao 1983; Van Impe 1989; Raithel et al. 2002; Ayadat and Hanna 2005; Murugesan and Rajagopal 2007; Black et al. 2007; Malarvizhi and Ilamparuthi 2007; Wu and Hong 2008). Although the external reinforcement in the form of encapsulating the column with a geofabric or with a rigid casing pipe, will prevent the column failing by bulging or by shear, it will not allow the column to dilate and accordingly to increase the in situ stresses (Ayadat and Hanna 2008). This technique can be limited by the relatively large settlements that occur as a result of minimal compaction (to avoid damage to geotextile encasement material) received during installation and geotextile strain during loading (Gniel and Bouazza 2008). Hence, there is a need to identify the effective and alternate methods which should be practically feasible to enhance the performance of stone columns in very soft soils.

An alternative method is suggested in this paper to enhance the performance of stone columns in soft soils by inserting nails (small diameter steel bars) vertically along the circumference of the stone column. Series of laboratory model tests were performed in a circular unit cell tank with the stone column at the centre and the soft soil surrounding it, to investigate the effect of vertical circumferential reinforcement on the strength, stiffness and bulging characteristics of stone columns in a soft soil bed. Load tests were carried out on unreinforced stone columns and stone columns reinforced with vertical circumferential nails to compare their relative performances. The influence of parameters such as depth of nails from the ground level, the number of nails, the diameter of nails, the diameter of stone column and area ratio are being studied.

2 Experimental Programme

Unit-cell idealization is used in the present study to simplify the design of the apparatus needed to assess the behavior of an interior column in a large group of columns. For an infinitely large group of stone columns subjected to a uniform loading applied over



Uniform load applied on the composite ground
(a)

Influence zone of each column (approximated as circle) is modelled as Unit cell
(b)

Unit cell with smooth, rigid radial boundary & rigid base
(c)

Fig. 1 Unit cell idealization

the area (Fig. 1a), each interior column may be considered as a unit cell as shown in Fig. 1b. Due to symmetry of load and geometry, lateral deformations cannot occur across the boundaries of the unit cell, and the shear stresses on the outside boundaries of the unit cell must be zero (Barksdale and Bachus 1983). Following these assumptions a uniform loading applied over the top of the unit cell must remain within the unit cell. The unit cell can be physically modeled as a cylindrical shaped container having a frictionless, rigid exterior wall symmetrically located around the stone column (Fig. 1c). Charles and Watts (1983); Ambily and Gandhi (2007); Gniel and Bouazza (2008) have used this concept of unit cell in their model testing to predict the behavior of stone column in a large group.

All experiments were carried out on 90, 75 and 60 mm diameter stone columns surrounded by soft clay in cylindrical tanks of 750 mm high and diameters varying from 158 to 283 mm to represent the required unit cell area of soft clay around each column assuming equilateral triangular pattern of installation of columns. It is well known that the bulging in the stone column happens predominantly at its top end (Hughes et al. 1975). Hence it was envisaged that reinforcing top end of the column is sufficient to promote additional load carrying capacity in the stone column. The depth of nails (*h*) was varied from 2 to 5 times the diameter of stone column, from the top. The number of nails (*n*) was varied from 6 to 10. The performance and bulging characteristics of stone column are significantly dependent on the area ratio, *Ar* (quantifies the amount soil replaced by stones, which is defined as the ratio of stone column area to the unit cell area), or spacing of the columns. Hence the tests were conducted with three different practical area ratios; 10, 15 and 23%, which correspond to spacings of 3*D*, 2.5*D* and 2*D*, respectively, where *D* is the diameter of the stone column. The other parameter considered is the diameter of the nails (*d*); which was varied by using 2 and 4 mm diameter steel bars. In the field, the entire plan area of the stone column treated ground will be subjected to loading from the superstructure. The same was simulated in the laboratory by loading the whole area of the unit cell. These tests are used to study the stiffness of improved ground. Tests with column area alone loaded are used to find the limiting axial stress of the stone column. Since the loading is rapid, it is essentially undrained loading which simulates loading immediately after construction. The overall experimental programme is given in Table 1.

A typical test arrangement is shown in Fig. 2. All the experiments were conducted on floating stone columns in soft soil in unit cell tanks so that *L/D* ratio (length of the column/diameter of the column) is a minimum of 6, which is required to develop the full limiting axial stress on the column (McKelvey et al. 2004). The total height of the clay bed placed in the tank was 8 times the diameter of the column. Vertical stress was applied either over the entire tank area or only over the stone column. The load was applied through a proving ring at a constant displacement

Table 1 Experimental Programme

Test description	Dia. of nails (*d*)	No. of nails (*n*)	Depth of nails (*h*)	Area ratio (*Ar*)/diameter of stone columns (*D*)					Total no. of tests
				$Ar = 10\%$	$Ar = 15\%$			$Ar = 23\%$	
				90 mm	90 mm	75 mm	60 mm	90 mm	
Only soil	–	–	–	–	–	–	–	–	3
Unreinforced stone columns	–	–	–	√	√	√	√	√	10
Stone columns with vertical circumferential nails	4 mm	8	2D		√	√	√		6
			3D	√	√	√	√	√	10
			4D		√	√	√		6
			5D		√	√	√		6
		6	3D		√	√	√		6
		10	3D		√	√	√		6
	2 mm	8	3D		√	√	√		6

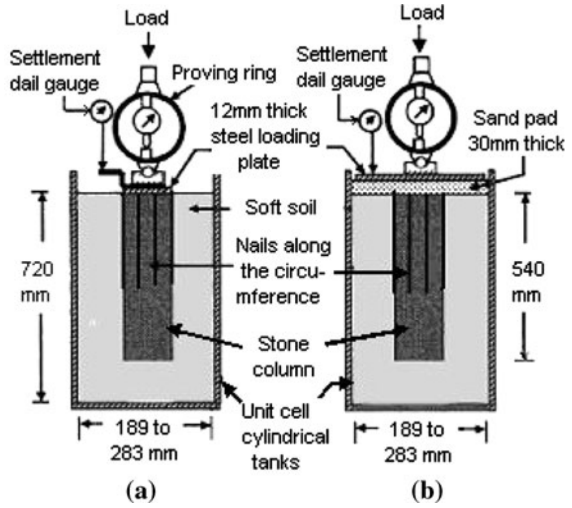


Fig. 2 Test arrangement −90 mm diameter stone column **a** Load applied only on column area **b** Load applied on entire area

rate. A 30 mm thick sand layer was placed at the top to serve as a blanket for the case where the entire area is loaded. The load was applied through a 12 mm thick mild steel plate.

2.1 Properties of Materials Used

The soft soil used is of ML classification, obtained from Kavoor near Mangalore, India. Particle size distribution is shown in Fig. 3. Other properties of soft soil and the soft soil bed are given in Table 2. Based on the preliminary tests on the soft soil, water content of 40% and dry unit weight of 12.8 kN/m^3 were selected for the soft soil bed and the corresponding shear strength of the bed was found to be 38 kPa. Aggregates of 2 to 10 mm particle size have been used to form the stone column. The maximum and minimum dry unit weights of the aggregate are determined as per the procedure laid down by the Bureau of Indian standards (IS 2720, Part 14-1983) and are found to be 16.5 and 14.1 N/m^3, respectively. The sand used is clean river sand of size less than 4.75 mm. The grain size distribution curve of the sand used is also shown in Fig. 3. Circular steel bars of 2 and 4 mm diameter of required length were used as nails along the circumference of the stone column.

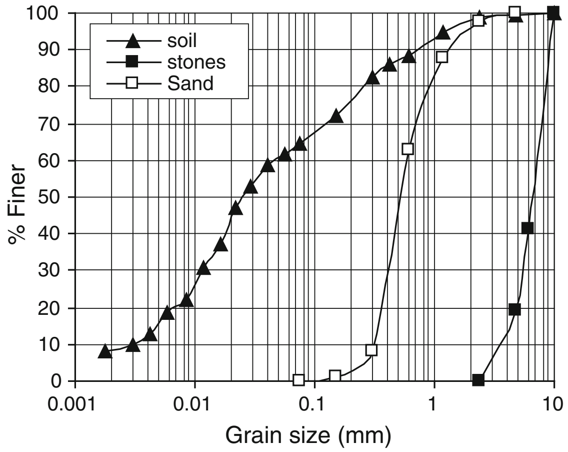


Fig. 3 Grain size distribution for soft soil, stones and sand used in the study

Table 2 Properties of soft soil and soft soil bed used in the study

	Property	Value
Soft soil	Specific gravity	2.6
	Liquid limit (%)	47
	Plastic limit (%)	34
Soft soil bed	Moisture content (%)	40
	Dry unit weight (kN/m^3)	12.8
	UCC strength (kPa)	38

2.2 Preparation of Soft Soil Bed and Construction of Stone Column

The inner surface of tank wall was covered with a very thin polythene sheet and a thin coat of grease was applied to reduce the friction between clay and the tank wall. Soil was filled in the tank in layers with measured quantity by weight. Each layer was subjected to uniform compaction with a tamper to achieve 50 mm height and unit weight of 12.8 kN/m^3. All stone columns were constructed by a replacement method. Thin open-ended seamless steel pipes of 90, 75 & 60 mm outer diameters and wall thickness 2 mm were used to construct the stone columns. After the soft soil bed was prepared for a depth of twice the diameter of the column, the steel pipe was placed at the centre of the soft soil bed and construction of soft soil bed and stone column were carried out simultaneously. Outer surface of the pipe was lubricated by applying a thin layer of grease for easy withdrawal without any significant disturbance to the surrounding soil. Stones were charged into the hole in layers in measured quantities (0.51 kg for 90 mm column) to achieve a compacted height of 50 mm. The pipe was then raised in stages ensuring a minimum of 5 mm penetration below the top level of the placed gravel. To achieve a uniform unit weight, compaction was done with a 2 kg circular steel tamper with 10 blows of 100 mm drop to each layer. This light compaction effort was adopted to ensure that there is no significant lateral bulging of the column which creates disturbance to the surrounding soft clay. The corresponding unit weight of stone column was found to be 16 kN/m^3. The procedure was repeated until the column was completed to the full height. After the construction of stone column, the required number of nails was inserted at equal spacing along the circumference of the stone column. Care was taken to ensure such that all nails were inserted vertically along the circumference of the stone column.

2.3 Test Procedure

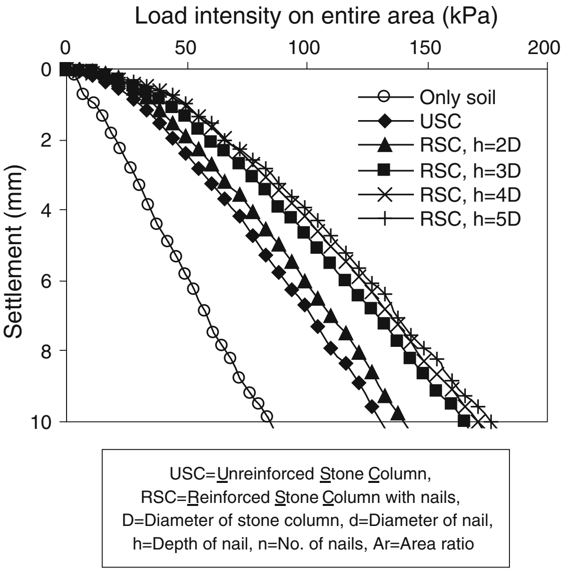
The load-deformation behavior of the column/treated soil has been studied by applying vertical load with the help of a loading frame. To load the stone column area alone, a loading plate of diameter equal to the diameter of the column was placed over the stone column. The load was applied through a proving ring at a constant strain rate of 1.2 mm/min. Settlements were monitored for equal intervals of loads up to failure. In the case where load is applied over the entire area, a 30 mm thick sand layer was placed over the entire surface. A steel plate of 12 mm thickness and a diameter of 10 mm less than the inside diameter of the test tank was placed over the sand blanket. The loading was applied in a similar way until the settlement exceeded 10 mm. After completion of each test, the shape of the stone column was established by pouring concentrated slurry of cement into the stone column and allowing it to set for about a day. After the slurry got hardened, the surrounding clay was removed carefully and the deformed shape of stone column was obtained and quantified.

3 Results and Discussions

3.1 Effect of Nails on Stiffness Behavior (Entire Area Loaded)

This analysis aims at evaluating the improvement in the stiffness of the treated ground with reinforced stone columns vis-à-vis plain or unreinforced stone columns. As discussed earlier, the loading of entire area of unit cell tank represents an actual field condition for the interior columns of a large group of stone columns. The performance of stone columns was investigated by reinforcing it only in the top portion of the columns with vertical circumferential nails to different depths. Figure 4 shows typical load-settlement behavior of improved ground with 90 mm diameter stone column, with and without vertical circumferential nails of 4 mm diameter (8 nos), for different depths of embedment (from 2*D* to 5*D*), for an area ratio of 15%. When the entire area is loaded, because of the confining effect from the boundary of the unit cell, failure does not take place even for a settlement of up to or beyond 10 mm.

The load carrying capacity (for 10 mm settlement) of treated ground with unreinforced and reinforced stone columns with 2*D*, 3*D*, 4*D* and 5*D* depth of embedment nails are increased by 54, 66, 98, 104 and 109%, respectively compared to that of untreated ground. It can be seen that a stone column reinforced with vertical circumferential nails to a depth three times the diameter of the column exhibits much higher load carrying capacity than unreinforced stone column. The increase in load carrying capacity beyond 3D depth of embedment is insignificant (only 6% improvement is observed between 3D and 4D depth of nails and



USC=Unreinforced Stone Column,
RSC=Reinforced Stone Column with nails,
D=Diameter of stone column, d=Diameter of nail,
h=Depth of nail, n=No. of nails, Ar=Area ratio

Fig. 4 Effect of depth of nails on load-settlement behavior. ($D = 90$ mm, $Ar = 15\%$, For RSC; $d = 4$ mm, $n = 8$)

5% between 4D and 5D depth of nails). Hence the depth of embedment of the vertical circumferential nails can be restricted to 3*D*, from economy point of view. This shows that the confinement is needed only where bulge takes place. Similar trend is observed for 75 and 60 mm diameter stone columns.

To evaluate the improvement in stiffness of treated ground, stiffness ratio (β), defined as the ratio of load intensity of treated ground to that of untreated ground, for the same settlement, was calculated and compared. Figure 5 shows the variation of stiffness ratio (corresponding to 10 mm settlement) with depth of nails for different diameter of stone columns. For all the diameter of stone columns, the stiffness ratio is increasing significantly with depth of nails up to 3D and thereafter up to 5D there is only a small and insignificant increase.

Figure 6 shows typical load-settlement behavior from model tests for different number of nails i.e. 6 to 10 for 90 mm diameter stone column with 15% area ratio. The load carrying capacity (for 10 mm settlement) of treated ground with unreinforced and reinforced stone columns with 6, 8 and 10 number of nails are increased by 54, 64, 98 and 110%, respectively compared to that of untreated ground. It can be seen that the load carrying capacity increases with the increase in number of nails. This may be due to the increased confinement of aggregates in the stone column with the increase in number of nails. Figure 7 shows the variation of stiffness ratio (corresponding to 10 mm settlement) with number of nails for different diameter of stone columns. For all the diameter of stone columns, the stiffness ratio is increasing significantly with number of nails.

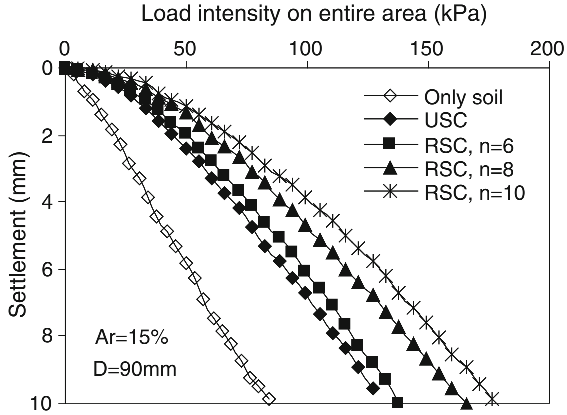


Fig. 6 Effect of number of nails on load-settlement behavior. (For RSC; $d = 4$ mm, $h = 3$D)

The effects of nails on different diameter of stone columns are clearly seen in Figs. 5, 7, 8, 9 and 10. Figure 8 shows typical load-settlement behavior of improved ground with different diameter stone columns with and without vertical circumferential nails of 4 mm diameter (8 nos), with embedment depth of 3*D*, for an area ratio of 15%. The nails are found to be more effective for smaller diameter stone columns. The increase in load carrying capacity (for 10 mm settlement) for 90 mm diameter stone column reinforced with nails is almost 100% more than that of untreated ground, compared to about 50% for unreinforced stone column. Whereas the load carrying capacity for 60 mm diameter stone column reinforced with nails is about 250% more than that of untreated ground against about 120% for unreinforced stone column. This may be due to the decrease in absolute

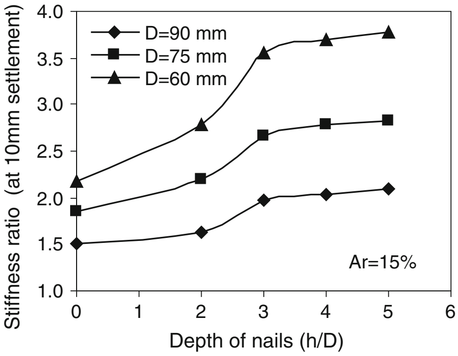


Fig. 5 Effect of depth of nails on stiffness ratio (For RSC; $d = 4$ mm, $n = 8$)

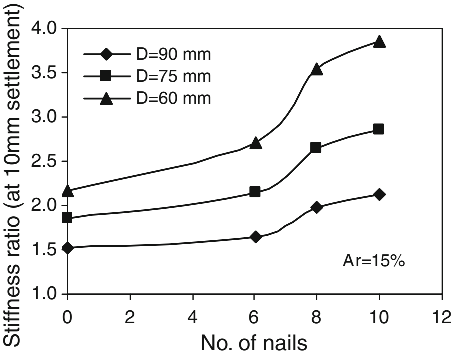


Fig. 7 Effect of number of nails on stiffness ratio (For RSC; $d = 4$ mm, $h = 3$D)

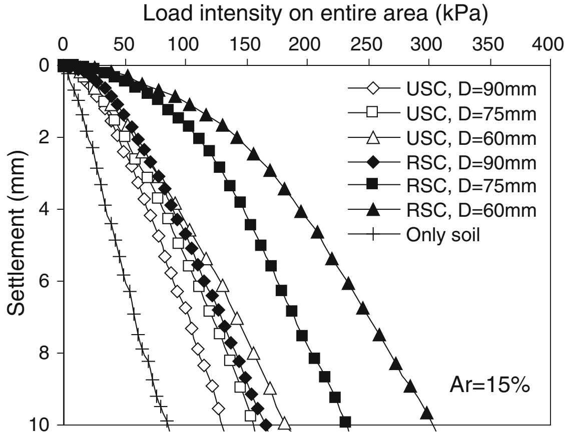


Fig. 8 Effect of diameter of stone column on load-settlement behavior. (For RSC; $d = 4$ mm; $n = 8$, $h = 3$D)

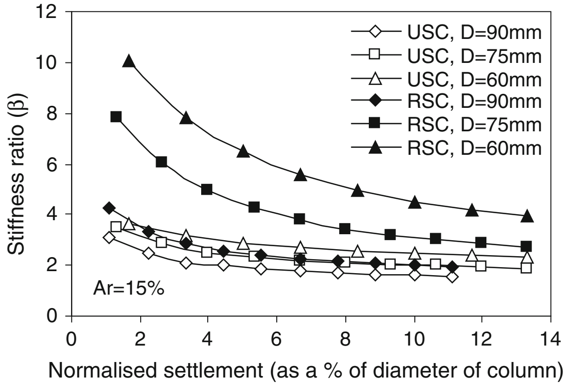


Fig. 9 Effect of diameter of stone column on stiffness ratio. (For RSC; $d = 4$ mm; $n = 8$, $h = 3$D)

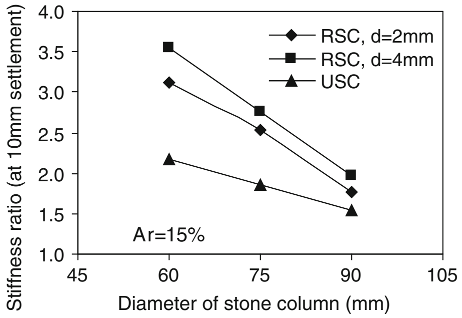


Fig. 10 Effect of diameter of nail on stiffness ratio (For RSC; $n = 8$, $h = 3$D)

spacing of nails in case of smaller diameter columns (for the same number of nails), and hence increase in the confinement.

Figure 9 shows the variation of stiffness ratio (β) with normalized settlement (ratio of settlement to the diameter of stone column) for different diameter of stone columns reinforced with and without vertical circumferential nails (4 mm diameter, 8 nos & 3*D* depth of embedment), for an area ratio of 15%. For reinforced stone columns, the stiffness increases significantly with the decrease in the diameter of stone column, for all the settlement levels. The stiffness ratio is higher at initial settlements and attains almost a constant value with the increase in settlements for all the diameters. When the compressive load is applied on the composite ground, the stone column tries to bulge laterally in the upper layers. The lateral bulging of stone columns gets significantly reduced due to the insertion of the nails. The top of nails also moves outwards slightly in the process of restricting the bulging of the stone column. Hence the stiffness ratio decreases as settlement increases initially and thereafter the passive resistance offered by the surrounding soil tends to keep the stiffness nearly constant. However, the stiffness ratios are considerably high for reinforced case as compared to unreinforced case. Figure 10 shows the variation of stiffness ratio (corresponding to 10 mm settlement) with the diameter of stone column for different diameter of nails. The improvement is seen to be further enhanced with the increase in the diameter of nail. This is due to the increase in stiffness of nail with the diameter.

The effect of nails on stone columns of different area ratios was also analyzed. Figure 11 shows typical load-settlement behavior of improved ground with 90 mm diameter column, for area ratios of 10, 15 & 23%, reinforced with 8 nails of 4 mm diameter, with embedded depth of 3*D*. The nails are found to be more effective for smaller area ratios. The increase in load carrying capacity (for 10 mm settlement) for 90 mm diameter reinforced stone column with vertical circumferential nails with 10% area ratio is almost 75% more than that of untreated ground, compared to about 25% for unreinforced stone column. Whereas the load carrying capacity (for 10 mm settlement) for 90 mm diameter reinforced stone column with vertical circumferential nails with 23% area ratio is almost 140% more than that of untreated ground, compared to about 100% for unreinforced stone column. Hence, these nails can be advantageously used for stone columns which are

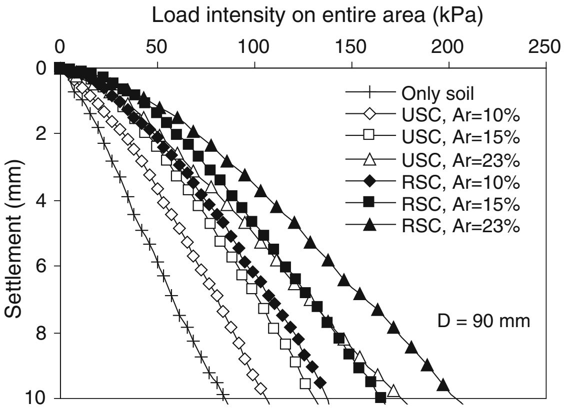


Fig. 11 Effect of area ratio on load-settlement behavior. (For RSC; $d = 4$ mm; $n = 8$, $h = 3D$)

placed at wider spacing and thus economy can be achieved. Figure 12 shows the variation of stiffness ratio (β) with normalized settlement for different area ratios, for 90 mm diameter stone column. It is observed that the stiffness increases significantly with the increase in area ratio both for reinforced and unreinforced stone columns, at all the settlement levels.

3.2 Effect of Nails on Limiting Axial Stress (Column Area Alone Loaded)

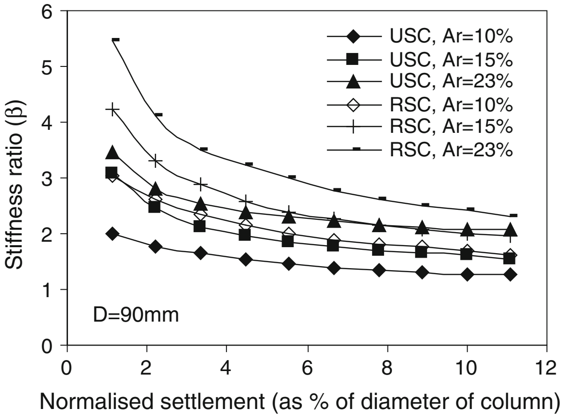


Fig. 12 Effect of area ratio on stiffness ratio (For RSC; $d = 4$ mm; $n = 8$, $h = 3D$)

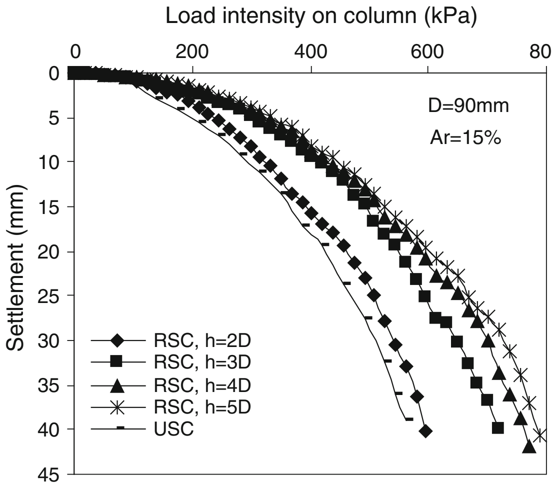


Fig. 13 Effect of depth of nails on load-settlement behavior (For RSC; $d = 4$ mm, $n = 8$)

Model tests were carried out with load applied just on the column area to find the limiting axial stress of the stone column. Figure 13 shows a typical relationship between axial load intensity on column and settlement for 90 mm diameter stone column, for an area ratio of 15%, reinforced with 8 nails of 4 mm diameter, with different depths of embedment. The limiting axial stress of the column reinforced with vertical circumferential nails, with 2*D*, 3*D*, 4*D* and 5*D* depth of embedment are increased by 6, 28, 37 and 41%, respectively compared to that of unreinforced stone columns. The limiting axial stress of reinforced stone column increases with the increase in depth of embedment of nails. This may be due to increased anchorage of nails with the increased depth of embedment into the soil, and decreasing the bulging tendency of stone columns and hence the limiting capacity.

Figure 14 shows a typical relationship between axial load intensity and settlement for 90 mm diameter stone column, for an area ratio of 15%, reinforced with 4 mm diameter, embedded over a depth of 3*D*, with different number of nails. As the number of nails increases, the limiting axial stress increases. The limiting axial stress of stone column with 6, 8 and 10 number of nails are increased by 13, 28 and 34%, respectively compared to that of unreinforced stone columns. Figure 15 shows a typical relationship between axial load intensity and settlement for 90 mm diameter stone column, for an area ratio of 15%, reinforced with 8 nails of 2 & 4 mm diameter, embedded over a depth of 3*D*. As the diameter of nails increases the limiting axial stress of stone column increases. The limiting axial stress of stone column with 2 & 4 mm diameter nails are

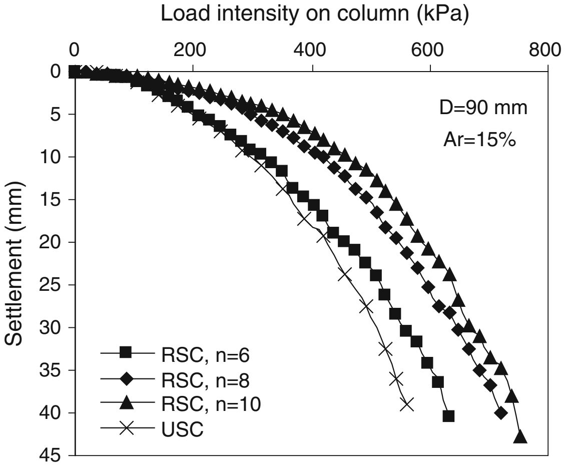


Fig. 14 Effect of number of nails on load-settlement behavior (For RSC; $d = 4$ mm, $h = 3D$)

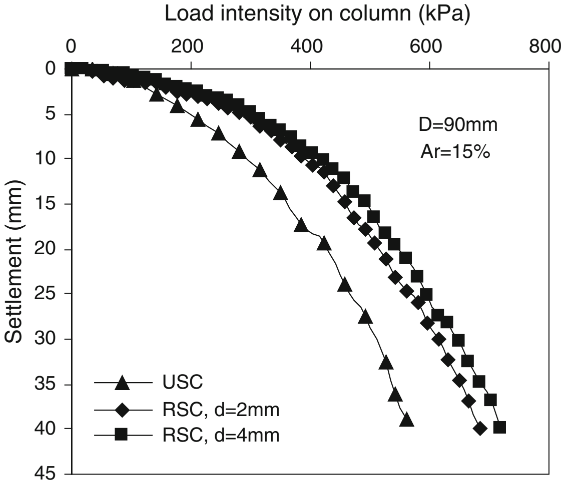


Fig. 15 Effect of dia of nails on load-settlement behavior (For RSC; $n = 8$, $h = 3D$)

increased by 21 & 28%, respectively compared to that of unreinforced stone columns.

Figure 16 shows a typical relationship between axial load intensity and settlement for different diameter of stone columns for an area ratio of 15%, reinforced with 8 nails of 4 mm diameter nails, embedded over a depth of $3D$. The influence of nails is more pronounced with smaller diameter stone columns. In other words, limiting axial stress of reinforced stone column increases with increase in ratio of diameter of nail to diameter of stone column.

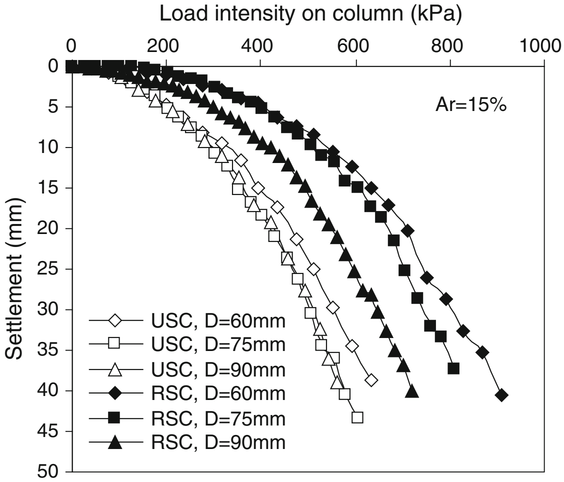


Fig. 16 Effect of diameter of stone columns on load-settlement behavior (For RSC; $d = 4$ mm; $n = 8$, $h = 3D$)

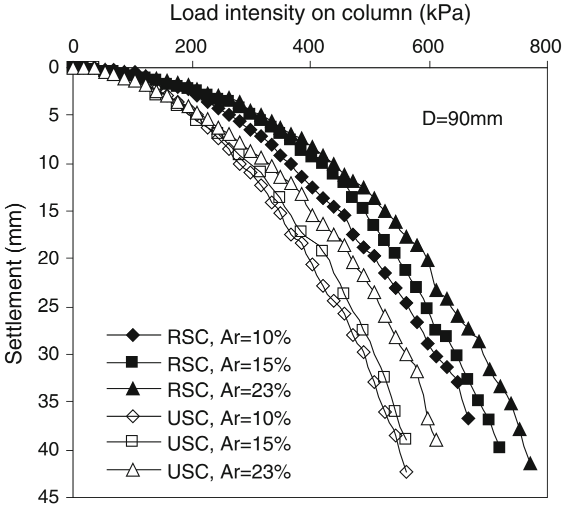


Fig. 17 Effect of area ratio on load-settlement behavior (For RSC; $d = 4$ mm; $n = 8$, $h = 3D$)

The limiting axial stress of reinforced stone columns of diameters 90, 75 and 60 mm are increased by 28, 35 & 44%, respectively compared to that of respective plain stone columns. Figure 17 shows a typical relationship between axial load intensity and settlement for 90 mm diameter stone columns for area ratios of 10, 15 & 23%, reinforced with 8 nails of 4 mm diameter nails, embedded over a depth of $3D$. Limiting axial stress increases with increase in the area ratio for both unreinforced and reinforced cases, although the difference for different area ratios is not very significant.

3.3 Bulging Behavior of Reinforced Stone Columns

After the load test, the deformed shape of the stone column was established by pouring concentrated slurry of cement into the stone column and allowing it to set for about a day. After the slurry gets hardened, the surrounding clay was carefully removed and the deformed shape was obtained. The diameter of the deformed stone column or bulge diameter was measured at different depths from the top of the column. The length of the deformed portion of the column was also measured. In case of unreinforced stone columns, the bulging mode of failure was clearly seen in tests where the column alone was loaded. Maximum bulging in this case was observed at a depth of 0.5 to 0.8 times the diameter of the column from the top. In case of stone columns reinforced along the circumference with vertical nails, the diameter and depth of bulging was significantly reduced for all the diameters of stone columns studied. No significant bulging was noticed when the entire tank area was loaded. Typical photographs of extruded stone columns are shown in Fig. 18.

Figure 19 shows the non-dimensionalised bulge profiles (bulging expressed as percentage of the diameter of stone column) for unreinforced and reinforced 90 mm diameter stone columns with 4 mm diameter nails (8nos & 3D depth), for different area ratios subjected to column area loading. The profiles show the variation of the non-dimensionalised bulge with normalized depth (H/D), where H is the total length of the stone column and D is the diameter of the stone column. For unreinforced stone columns, bulging decreased with the increase in area ratio. The maximum bulging was found to occur at a depth of 0.5 to 0.8 times the diameter of the column from the top. The total length of the stone column subjected to bulging was observed to be 2 to 3 times the diameter of the column for different area ratios. For reinforced stone columns, the diameter and length of bulging was significantly reduced compared to that of plain stone columns. The maximum bulging for 10, 15 & 23% area ratios are found to be 12.7, 10.6 & 6.8%, respectively for 90 mm diameter unreinforced stone column and it decreased to 5.0, 3.9 & 2.3% for reinforced stone column. Thus, more than 60% of bulging is reduced due to insertion of vertical circumferential reinforcement.

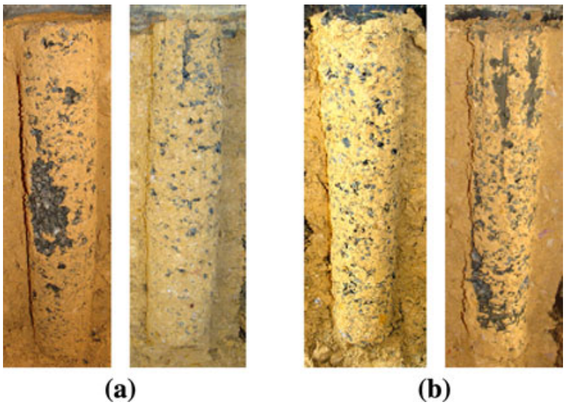


Fig. 18 Deformed shape of unreinforced & reinforced stone column. ($D = 90$ mm, $Ar = 15\%$, For RSC; $d = 4$ mm, $n = 8$, $h = 3D$). **a** Entire area loading, **b** Column area loading

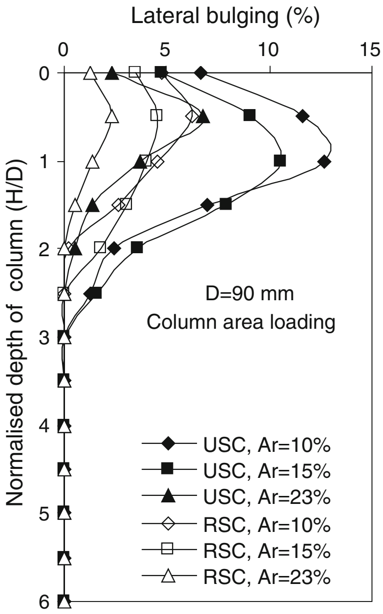


Fig. 19 Effect of area ratio & nails on bulging (For RSC; $d = 4$ mm; $n = 8$, $h = 3D$)

In case of unreinforced stone columns, for the same area ratio, the bulging increased with the decrease in the diameter of stone columns. From Fig. 20, for 15% area ratio the maximum bulging was found to be 10.6, 14.9 & 19.4% for 90, 75 & 60 mm columns, respectively and it decreased to 3.9, 4.0 & 3.5% when they are reinforced with 4 mm nails

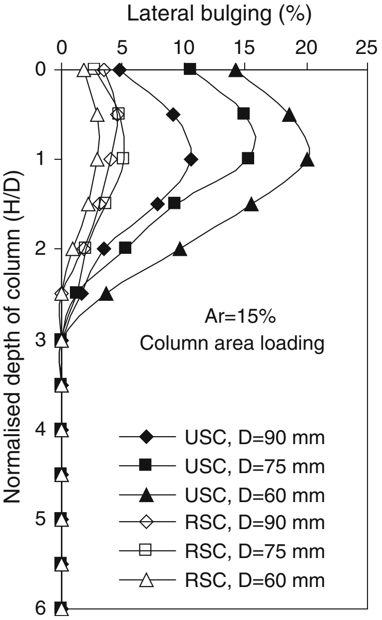


Fig. 20 Effect of diameter of stone column & nails on bulging (For RSC; $d = 4$ mm; $n = 8$, $h = 3$D)

(8 nos & 3*D* depth) along the circumference. The corresponding decrease in maximum bulging for 90, 75 and 60 mm diameter columns are 63, 73 & 82%, respectively. It can be seen that the decrease in bulging was more pronounced for lower diameter stone column.

4 Conclusions

An alternative and effective method of enhancing the performance stone columns installed in soft soils is suggested in the form of encasing the individual stone column with vertical circumferential nails. The main advantage of these nails is that they can be easily driven at site after the stone columns are installed. These circumferential nails impart substantial lateral confinement to the stone column, enabling a stiffer and stronger response. Although the tests were carried out using reduced-scale models, the results give some important insight into the performance of stone columns reinforced with vertical circumferential nails. From the results of these tests, the following conclusions can be drawn.

1. Stone columns reinforced with vertical circumferential nails exhibit a stiffer and stronger response compared to that of conventional stone columns installed in soft soil, for all the diameters and area ratios studied. The performance is significantly enhanced by increasing the number of nails and diameter of nails.
2. Stone column reinforced with vertical circumferential nails over a depth thrice the diameter (3*D*) exhibits much higher stiffness and ultimate load capacity than unreinforced stone column for all the diameters studied. Studies have shown that the confinement is needed only where bulging takes place.
3. For a particular settlement, both reinforced and unreinforced stone columns exhibit higher load intensity for smaller diameter stone columns. The benefit of vertical circumferential nails decreases with increase in the diameter of stone columns, for the same number of nails of specific diameter.
4. The nails are found to be more effective for smaller area ratios. Hence, nails can be advantageously used for stone columns which are placed at wider spacing and thus economy can be achieved.
5. Bulge diameter and bulge length are decreased substantially for a stone column reinforced with vertical circumferential nails compared to that of unreinforced stone columns for all the diameters and area ratios studied.

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