TECHNICAL PAPER

Experimental evaluation of stress concentration ratio of soft soil reinforced with stone column

G. Kumar[1,2] · M. Samanta[1,2]

Abstract

Ground improvement using stone column reinforcement is an effective treatment technique to increase the stiffness and reduce the total and differential settlement of the soft deposits. Even though stone column reinforcement is a well-established technique, detailed experimental study regarding the load-sharing characteristics and parameters influencing the stress concentration ratio (SCR) between the soil and column is very limited. In the present study through a systematic laboratory investigation, time-dependent and peak SCR between the stone column and surrounding soil has been evaluated for a practical range of stone column, surrounding soil, top sand blanket thickness and column material properties. Stress experienced from the foundation loading to stone column and surrounding soil in a unit cell has been measured using earth pressure cells. Peak SCR has been observed to be in the range of 4–6 for the set of material parameters investigated in the present study. Peak SCR is in the range of 4–5.5 when internal friction angle of the stone column material varies from 38° to 42°. SCR is significantly influenced by the thickness of the top sand blanket. However, an insignificant influence of sand blanket material properties on the SCR has been observed. Additionally, surrounding soil strength significantly influences the SCR of the composite system. The results of the present study will be useful for the estimation of stiffness and settlement of the stone column-reinforced composite ground.

Keywords Soft soil improvement · Stress concentration ratio · Angle of internal friction · Composite system · Sand blanket · Unconfined compressive strength

Introduction

Stone column is an effective and economic in situ ground-reinforcing technique to improve the strength and stiffness of the soft clay deposits. Installation of stone column increases the bearing strength, accelerates the consolidation mechanism and reduces the consolidation time in the case of soft soils. Stone columns are successfully used to support the earthen embankment, LPG storage tank, raft foundation and bridge approach fill. A large numbers of analytical,

laboratory and field studies had contributed in greater understanding of settlement, bearing capacity and deformation behaviour of the stone column-reinforced ground [1–20].

Analytical and numerical studies show that the stress concentration ratio (SCR), i.e. the ratio of stress carried by the stone column to the surrounding soil, significantly influences the consolidation behaviour of the stone column-reinforced ground [7, 21–23]. However, an accurate determination of the stress concentration ratio plays an important role in estimation of the settlement and composite stiffness of the improved ground. Usually, field or experimental tests are performed to determine the SCR between the stone column and surrounding soil. For the usual range of properties of stone column and surrounding soil, the SCR varies in the range of 2–6 [24–26]. Based on the experimental and field test results, Barksdale and Bachus [27] suggested that the SCR between stone column and surrounding soil lies in the range of 3–10. Xueyi et al. [28] investigated the influence of addition of the dry sand, lime and cement separately with stone column material to examine the SCR through small-scale laboratory model tests. The

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loading condition is similar to foundation loading in the real field scenario. SCR between the stone column and surrounding soil was found to be in the range of 4–7.6. Also, the SCR was found to be dependent on the unconfined strength of the surrounding soil, stone column material and time elapsed after loading. Fattah et al. [29] performed model studies through instrumented load tests on single and group of stone column-reinforced soft soil to determine the SCR. Cement and sand were then added separately to the column material for strengthening the stone column. SCR was found to be in the range of 1.2–3.8 for different parameters and testing conditions adopted in the study. Poon and Chan [30] determined the SCR of the stone column through 2D finite element analysis. The stone column-improved ground was replaced with a strip of appropriate width and equivalent properties to represent the stone column-improved soil. The SCR was investigated along the length of equivalent strip for floating and end-bearing conditions. The SCR on the equivalent strip was also compared with the results from 3D and axisymmetry finite element analysis. Das and Deb [31] measured the SCR between the stone column and surrounding soil subjected to embankment loading. Earth pressure cell placed at the top of the stone column and surrounding soil was used to measure the stresses. The SCR was found to be dependent on the critical height of the embankment, time and modular ratio of the stone column and surrounding soil.

A sand blanket is usually placed at the top of the stone column-improved ground for uniform distribution of stress and also acts as a horizontal drain to dissipate the pore water. In the field, area replacement ratio of the stone column, properties of the stone column and surrounding soil, sand blanket thickness and material properties may vary over a wide range. However, studies on the influence of these parameters on the SCR between stone column and surrounding soil are very limited in the literature. In the present study, SCR between stone column and surrounding soil has been investigated through laboratory investigation using unit cell idealization. Earth pressure cells have been used to measure the stresses on the stone column and surrounding soil for the entire unit cell area loading conditions. Variation in the SCR with time has been investigated and reported in this paper. Time-dependent and steady-state SCR between the stone column and surrounding soil has been studied for a practical range of different parameters of stone column-reinforced soft soil, i.e. area replacement ratio, stone column material properties, top sand blanket thickness and its material properties and undrained shear strength of the surrounding soil.

Experimental study

Usually, stone columns are installed in triangular or square pattern in a group having certain influence area of each column. The equilateral triangle pattern is most commonly used since the influence area of a single column in triangular pattern is greater than the square pattern. The equivalent cylindrical influence area of a single column within a group of columns is called the unit cell. In the present experimental study, unit cell idealization of a single column within a group of columns has been used. All the laboratory tests are performed in a cylindrical tank representing the unit cell having 185 mm diameter and 600 mm height. Area replacement ratio, i.e. ratio of the area of a single column to its unit cell area/influence area, depends on the diameter, centre-to-centre spacing and pattern of the stone column in a group. In the present study, area replacement ratio has been calculated for triangular pattern of stone column arrangement in a group with centre-to-centre spacing of three times the diameter of stone column. Properties of the different materials used for stone column, soft soil test bed and top sand blanket are described below.

Soft soil medium (C)

To prepare the soft soil medium for stone column installation, soil sample was collected from nearby of Roorkee, Uttarakhand. The liquid limit, plastic limit and unit weight at optimum moisture content are 40%, 28% and 16.4 kN/m^3, respectively. The soil is classified as clayey silt of medium plasticity (CI – MI) as per Indian Standard Classification System (IS: 1498). Grain size distribution of the soil is shown in Fig. 1. The sample consists of 74% of silt and 26% of clay. The other properties of the sample are shown in Table 1. Unconfined compressive strength (UCS) has been used as an indicator/controlling parameter for the soft test
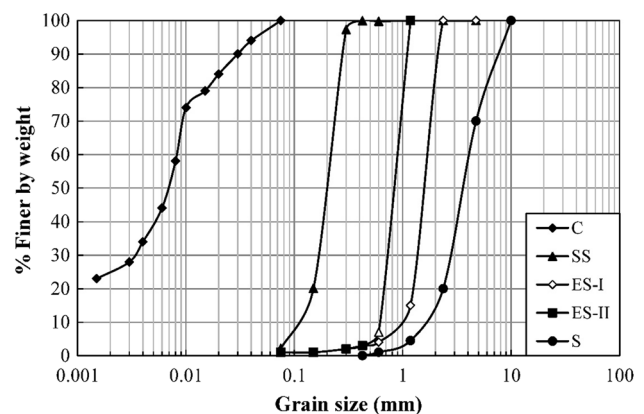

Fig. 1 Grain size distribution curves of different materials

Table 1 Properties of different materials

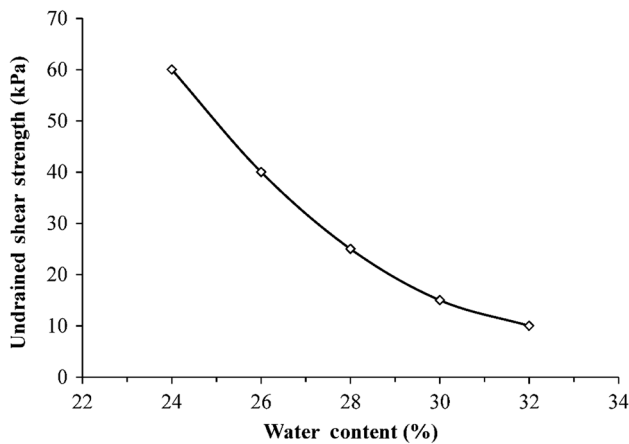| No.	Properties	Materials				
		SS	ES-I	ES-II	S	C
1	Specific gravity	2.67	2.64	2.64	2.6	2.8
2	Gravel (%)	–	–	–	30	–
3	Sand (%)	100	100	100	70	–
4	Silt (%)	–	–	–	–	74
5	Clay (%)	–	–	–	–	26
6	Coefficient of uniformity (C_u)	1.92	1.5	1.95	2.28	–
7	Coefficient of curvature (C_c)	1.15	0.91	0.95	0.57	–
8	Angle of internal friction (φ)	36°	38°	40°	42°	–
9	Optimum moisture content (OMC) %	–	–	–	–	14.4
10	Unit weight at OMC (kN/m^3)	–	–	–	–	16.4
11	IS classification	SP	SP	SP	SP	CI-MI

Fig. 2 Water content versus undrained shear strength of test medium

bed preparation. Initially, the variation in UCS with different water content has been evaluated preparing the sample in standard proctor compaction energy. Based on the test results, UCS and corresponding water content values are plotted. Figure 2 shows the variation in the UCS with water content. For the present study, UCS of the soft clay bed is fixed at 15 kPa. For 15 kPa UCS of the soft clay bed, the corresponding water required may be fixed using Fig. 2. Then, the required amount of water is mixed with the soil to get the necessary consistency.

Column/sand blanket material

Stone aggregates (S)

A mixture of sand and stone aggregates is used to form the stone columns only. The stone aggregates are angular granite chips of size in the range of 4.75–10 mm. The grain size distribution curve of the mix sample is also shown in Fig. 1. The mix sample consists of 70% sand and 30% gravel. The

mix sample can be classified as SP as per Indian Standard Classification System. The peak angle of internal friction of the mix is found to be 42°, evaluated through the large-size direct shear test. Other properties of the mix sample are listed in Table 1. For stone column formation, the mix sample was compacted to a unit weight of 16 kN/m³. The usual range of relative density of the stone column in the field varies in the range of 60–80% [4]. In the present study, the relative density of the finished stone column calculated from the consumption of material is found to be 70 ± 2%, which is well within the field density. It is expected that the small variation in the relative density of the stone column has an insignificant effects on the overall behaviour of the stone column-improved soft soil.

Sand

Three different types of sands are used as the stone column and top sand blanket material. Rounded Solani Sand (SS) obtained from nearby Solani River and two different Standard Ennore Sands (ES-I and ES-II) are also used as stone column and sand blanket material in the present study. The grain size distribution of the different sands are also shown in Fig. 1 All the sand has been classified as SP as per Indian Standard Classification System. SS sand consists of 100% fine-sized sand (0.425–0.75 mm). ES-I consists of 3% fine sand, 77% medium sand (2–0.425 mm) and 20% coarse sand (4.75–0.425 mm). ES-II consists of 3% fine sand and 97% medium sand. Different properties, i.e. coefficient of uniformity (C_u), coefficient of curvature (C_C) and internal friction angle, are given in Table 1. Angle of internal friction for the three different sands is evaluated through small-sized direct shear box at 75% relative density equivalent to stone column formation density usually adopted in the field. Three different sands and mix of sand and stone show a different angle of internal friction as shown in Table 1. Table shows that the angle of internal friction of three different sand
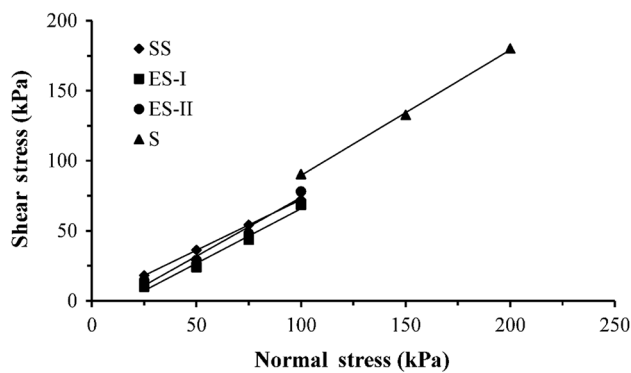
Fig. 3 Direct shear test results of different materials used in the study

materials varies in the range of 36°–40°. The shear strength vs normal stress relationship for the stone aggregates (S), Solani Sand (SS), Ennore Sand-I (ES-I) and Ennore Sand-II (ES-II) are shown in Fig. 3.

Preparation of soft bed

The soil was initially pulverized and oven dried for 24 h at 105° before the sample preparation. Then, the required quantity of water is added to the dry soil and mixed vigorously to produce a homogenous paste of required consistency. The main assumption in the unit cell idealization is that the vertical side of the unit cell acts as a frictionless boundary/roller support. In the present model study, to minimize the wall friction and boundary effects between the soft soil and vertical boundary of the unit cell, a thin coat of grease was applied on the vertical side of the unit cell before the filling of soft bed. Then, the prepared sample was transferred to the unit cell tank and placed in layers of uniform thickness to achieve the required consistancy. The unit cell was filled in five equal layers and each layer was properly compacted with a hammer of 45 N to achieve a compacted height of 120 mm. After compaction of each layer, undisturbed samples were taken out using a sampling tube to evaluate the in situ UCS and water content of the prepared soft bed. In situ water content and UCS of the prepared bed have been taken as quality control criteria of the prepared bed. A 5% variation in the UCS values of the prepared soft bed was considered to be acceptable in the present study. Prepared bed showing variation more than the above-mentioned criteria was prepared and checked again before the test.

Installation of stone column

Method of formation of stone column significantly influences the behaviour of the reinforced ground. Most commonly, replacement or displacement method of stone column formation is followed in the field/laboratory. In the

present study, stone column within the unit cell has been formed through replacement technique, i.e. removal of soil from unit cell tank using a casing pipe having outer diameter equal to the column diameter. Replacement technique has been proved to produce stone column of excellent consistency in small-scale model test [6]. Using guide plates, the pipe was pushed vertically through hydraulic jack into the prepared bed until it reaches the bottom of the tank. The soil inside the tube was then removed carefully leaving hole at the centre. The stone column is formed in five equal layers of 120 mm height each. The quantity of material required for each layer was calculated priori and placed inside the bore hole. Before placing, the materials are moistened at natural moisture content to prevent absorption of water from surrounding soil. Then, the material was compacted using a hammer to achieve the desired unit weight. Then, the casing tube was lifted ensuring a minimum depth of 25 mm below the top level of compacted stone aggregates to prevent the collapsing of the soil inside the hole. Current method of cased stone column formation is usually followed in the field where borehole stability is a problem due to high groundwater level or surrounding soft soil [27]. The above-mentioned procedure was repeated to complete the column up to the full height (Fig. 4). After column installation, the top surface was carefully levelled and remaining top soil was removed. After column installation, the top blanket was formed using sand pluviation method. The sand was poured from prefixed height to achieve a maximum density of 75% for the selected thickness.

Fig. 4 View of unit cell and complete stone column

Test procedure

After installation of the stone column, load tests were performed. For measuring the stress distribution, two miniature earth pressure cells, one at centre of stone column and other at the top surface of the soft soil, were placed. Capacity of the earth pressure is 500 kPa with an accuracy of 0.001 kPa. The location of earth pressure cells for typical load tests is shown in Fig. 5a. The load taken by the stone column or soft soil can be measured directly from a single earth pressure cell placed either on soft soil or stone column. The purpose of using two earth pressure cells in the present study is to validate the one earth pressure cell reading from other. Also, test can be useful even if one of the earth pressure cell malfunctioned during the test. After placing earth pressure cell, top sand blanket layer of 150 mm thickness was laid over the composite system. Typical completed view of the constructed stone column is shown in Fig. 5b. For evaluating SCR, surface loading test, i.e. loading plate having a diameter of 183 mm and a thickness of 3 mm, was selected and placed at the top of the sand blanket layer. The small difference in diameter between surface loading plate and unit cell is beneficial to avoid the internal friction between the side of loading plate and inner side of unit cell. A constant load of 1200 N was applied to the composite ground. During testing, the load was maintained constant till the settlement seizes or shows a rate less than 0.001 mm/min. The settlement of the composite system was measured through a set of three duly calibrated dial gauges placed at an angle of 120° with each other. The load coming to the composite system was measured through a load cell placed between the plunger of hydraulic jack and loading plate. The capacity of the load cell is 2.5 T with an accuracy of 0.001% of full-scale output. The complete loading arrangement for the test is shown in Fig. 5c. The reading of the earth pressure cells and dial gauges was continuously recorded and monitored through a 48-channel online data acquisition system. The following subsections describe the effects of different parameters of the stone column-reinforced composite ground on the SCR of the system. The methods of soft bed preparation, stone column formation, installation of earth pressure cells, top sand blanket formation and application of load remain the same for all the series of tests in the present study.

Results and discussions

The test program consists of five different series and a total of 21 surface loading tests where different parameters of the stone column-reinforced composite system were varied. The parameters include area replacement ratio of stone column, material properties of the stone column, sand blanket thickness, sand blanket material properties and undrained shear strength of the surrounding soil. For all the varying parameters, time-dependent and peak SCR (SCR_P) of the composite system has been studied. Table 2 shows the details of different parameters and number of tests performed in the present study.

Effect of area replacement ratio

Area replacement ratio plays an important role on the response of the composite ground. The settlement and bearing capacity of the stone column-reinforced ground primarily depend on the area replacement ratio. Usually, the area replacement ratio in the field varies in the range of 10–30% [4]. Area replacement ratio below 10% is not effective for ground improvement, and higher than 30% is not economical. In the present study, soft clay bed was reinforced with three different stone column diameters,
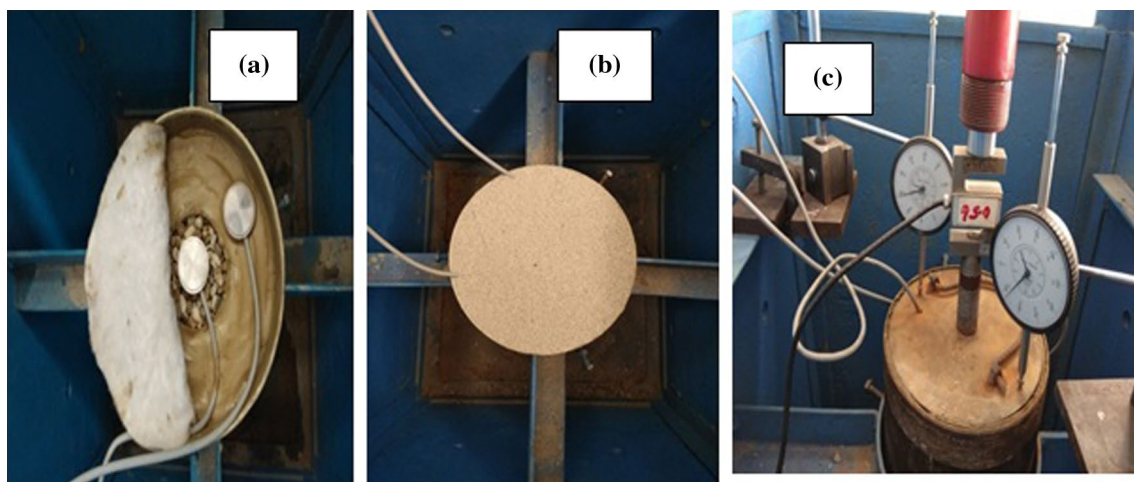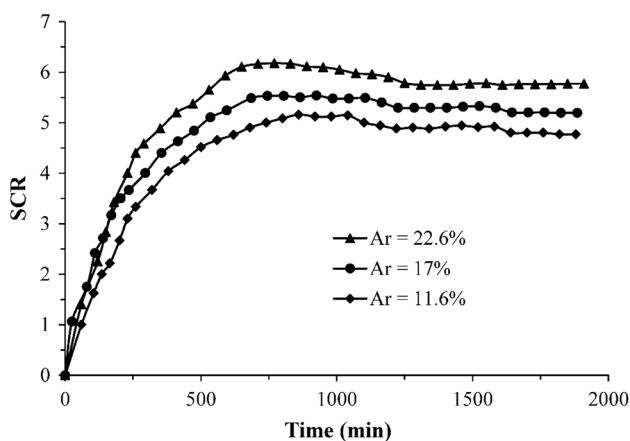

Fig. 5 Different stages of testing. **a** Location of earth pressure cell, **b** Placement of sand blanket layer, **c** Application of load

Table 2 Experimental program

Sl. no.	Parameters	Range	Number of tests
1	Area replacement ratio	11.6%, 17%, 22.6%	3
2	Angle of internal friction of stone column material	38°, 40°, 42°	3
3	Thickness of top sand blanket	150 mm (variation in angle of internal friction of stone column material of 38°, 40°, 42°) 300 mm (variation in angle of internal friction of stone column material of 38°, 40°, 42°) 450 mm (variation in angle of internal friction of stone column material of 38°, 40°, 42°)	9
4	Angle of internal friction of top sand blanket	36°, 38°, 40°	3
5	Undrained shear strength of surrounding soil	15 kPa, 30 kPa, 45 kPa	3
Total number of tests			21

Fig. 6 Variation in SCR with time for different area replacement ratios

i.e. 63 mm, 76 mm and 88 mm, representing area replacement ratios of 11.6%, 17% and 22.6%, respectively. For this series of test, mixture of sand and stone aggregates S has been used as stone column material having an angle of internal friction (φ) of 42°. Solani River sand SS of 150 mm thickness has been used as top sand blanket. The angle of internal friction of the SS is 36°. The applied load creates an average stress level of 120 kPa at the top surface of the composite ground. In the present study, time-dependent SCR and SCR_p of the composite system have been evaluated. Total consolidation settlement of the system can be calculated from the SCR_P. Also, from knowledge of the time-dependent SCR of the composite system, change in the consolidation properties of the surrounding soil can be employed in the analysis to realistically estimate the rate of consolidation and total settlement of the system. Figure 6 shows the variation in SCR with time for different area replacement ratios. A nonlinear behaviour of SCR with time has been observed for all the area replacement ratios. Initially, SCR increases rapidly with time and reaches the peak and then becomes almost constant. Accelerated consolidation of the stone column-reinforced soft soil started with the application of surcharge load. The consolidation results in a settlement and gradual transfer of load from soft soil to stone column. The gradual load transfer from soft soil to stone column results an increase in the SCR of the reinforced ground. Consolidation of the stone column-reinforced soft soil leads to the progressive vertical and lateral deformation of the stone column. When SCR reaches peak, the consolidation of the soft soil almost became complete and the deformation of the stone column and soft soil stops under given surcharge load. At completion of consolidation under given surcharge load, the SCR became almost constant. The observed peak values for the selected area replacement ratio ranges from 5.2 to 6.2, and columns with higher area replacement ratio show maximum values of SCR_P. For higher area replacement ratio, the presence of larger stone column carries majority of load, thus preventing the soft soil from experiencing excess pressure, which resulted in higher values of SCR. It can also be observed from the test results that the stress taken by columns increases with area replacement ratio, whereas the stress experienced by soil surface reduces [21].

SCR_P is plotted against the area replacement ratio in Fig. 7. The present results are also compared with the experimental results of Juneja et al. (2013). They investigated the SCR of the sand compaction pile-reinforced soft soil for different over-consolidation ratios (OCR) of surrounding soil through small-scale laboratory test. The test results from the present study show that a almost linear relationship exists between SCR_P and area replacement ratio. The range of SCR found in the present study matches well with the previous study. SCR and SCR_P are dependent on the area replacement ratio and plays a major role in transferring load between column and soil for stone column-reinforced ground.
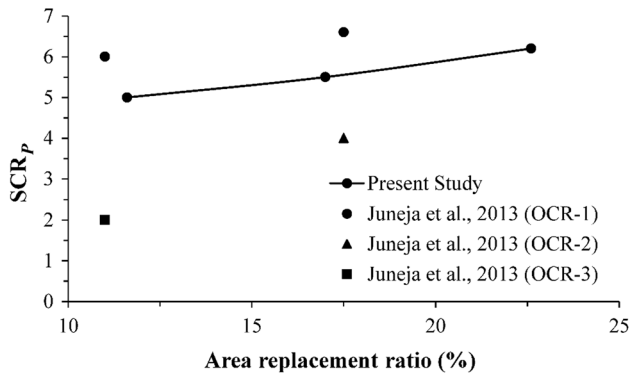
Fig. 7 Variation in SCR_P with area replacement ratio

Effect of column material property

Relative stiffness of the stone column and surrounding soil plays a major role in stress distribution between the column and surrounding soil [21]. In this series of test, the variation in SCR and SCR_p with the stone column material properties has been investigated. In this series of test, material with different angles of internal friction has been used as stone column while surrounding soil and top sand blanket thickness and material properties, applied stress level and area replacement ratio remain the same as described previously. SCR and SCR_p of the composite system have been evaluated for S, ES-I and ES-II as stone column material. Usually in the field, well-graded clean sand, mixture of sand and gravel are used as stone column material. The angle of internal friction of the stone column material to be used in the field should be in the range of 36°–44° [27]. In the present study, material having an angle of internal friction in the range of 38°–42° has been chosen as stone column material. Figure 8 shows the variation in SCR with time for different stone
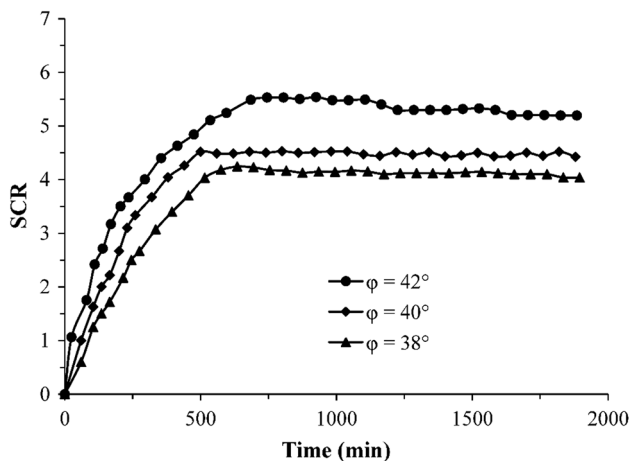
column materials. A similar variation in SCR with time as described previously is also observed in this case. The stone column material S (42°) shows the highest angle of internal friction followed by ES-I (40°) and ES-II (38°). Results show that the stone column made of S material shows the highest SCR followed by the ES-I and ES-II.

Figure 9 shows the variation in SCR_P with angle of internal friction of stone column material. Results show that SCR_P depends significantly on the angle of internal friction of stone column material and increases linearly with increase in the angle of internal friction of the stone column material. In the present study, SCR_P varies from 4.2 to 5.5 when angle of internal friction of the stone column material varies from 38° to 42°. A similar observation about the load sharing between different elements of the stone column-improved ground, and improvement in load bearing capacity with the variation in stone column material has also been reported by previous researchers. Relative stiffness of the stone column-reinforced soft soil increases with increase in the angle of internal friction of stone column material. Higher stiffness of stone column material attracts more load and shares a larger portion of load, which results in higher SCR. Das and Deb [31] from the experimental test on the stone column-improved soft soil-supported embankment also reported that the lower modular ratio causes poor transfer of stress, which leads to a reduction in SCR. Stone column material properties show a more pronounced effects on the SCR_P when compared with the area replacement ratio of the as evident from the slope of the graphs.

Effect of top blanket layer thickness

The top blanket layer laid over the composite system plays a significant role in load distribution. Selection of adequate thickness and material is essential since it ensure the load transfer mechanism between column and soil and also helps pore water pressure dissipation at top. As stresses near the
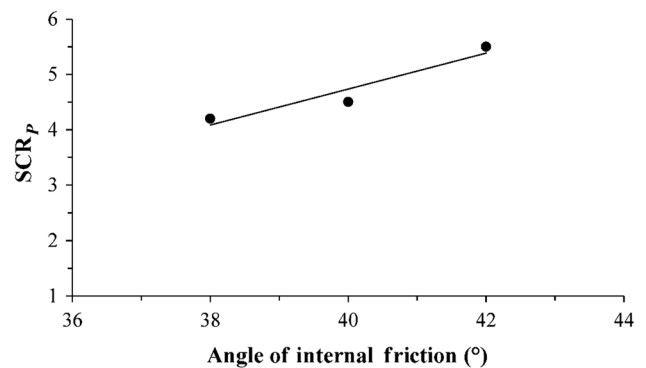

Fig. 8 Variation in SCR with time for different column materials ($A_r = 17\%$)

Fig. 9 Variation in SCR_P for different stone column materials ($A_r = 17\%$)

top of the treated group are significantly influenced by the presence of granular mat, hence it is important to consider the effect of the granular mat in composite system. As per authors' review, there are no experimental investigation performed on the load distribution mechanism due to the thickness of top blanket material layer and its material characteristics. In the present study, time-dependent SCR and SCR$_p$ are investigated for different top layer thicknesses. In this series of test, area replacement ratio was kept as 17% and top blanket layer was prepared with soil having an angle of internal friction of 38° at 75% density. SCR of the composite system has been investigated for 150 mm, 300 mm and 450 mm top sand blanket thicknesses and different stone column materials having an angle of internal friction angle in the range of 38°–42°. Figure 10 shows the variation in SCR with time for different stone column materials for top blanket thickness of 150 mm. A similar variation in SCR with time as described previously has also been observed for this case. Figure 11 shows the variation in SCR$_P$ with varying thickness of top blanket. The result shows that the SCR$_P$ decreases with the increase in the top blanket thickness for all the stone column material properties. Increasing the thickness of the top sand blanket is beneficial in reducing the applied stress level at the top of the stone column. This beneficial effect on the stone column is due to the settlement of the top sand blanket and uniform distribution of the load at the top of the stone column and surrounding soft soil. Due to this, SCR$_P$ reduces with increase in the top sand blanket thickness. As the stone column is the stiffer component and carries larger stress in the composite system, a suitable thickness of top blanket thickness reduces the stress in the column and prevents it from the local failure within the column. As stresses near the top of composite ground are high, provision of granular blanket of adequate thickness will result in reduction in SCR and subsequently SCR$_P$ and
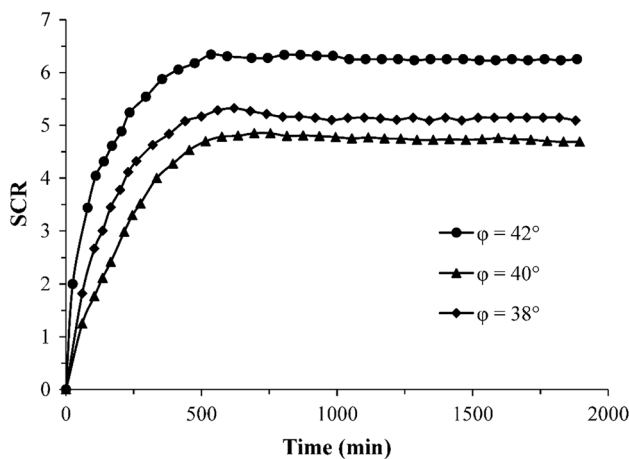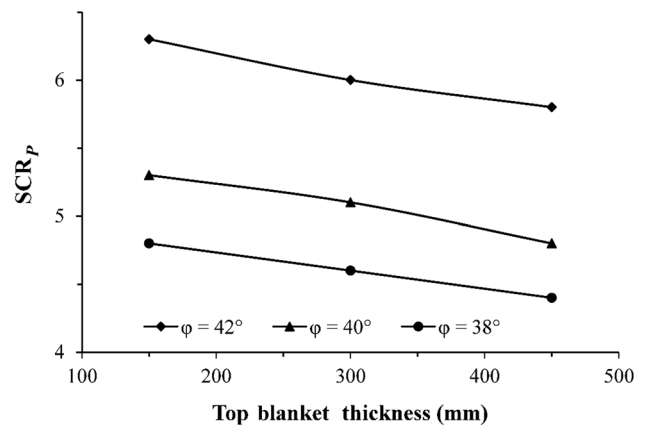

Fig. 11 Variation in SCR$_P$ versus thickness of top blanket layer for different column materials ($A_r = 17\%$)

prevent the column from reaching its yield capacity and failure can be controlled. This will be highly helpful where high area replacement ratio is not possible; provision of granular blanket will improve the performance of treated ground.

Effect of top blanket material property

In this series of test, time-dependent SCR and SCR$_P$ of the composite system have been investigated for the different material properties of top sand blanket. Material properties of the top sand blanket may vary over a wide range in the field. In this series of test area replacement ratio, top sand blanket thickness and applied load level are kept as 17%, 300 mm and 1200 N, respectively. SS, ES-I and ES-II having angle of internal friction of 36°, 38° and 40°, respectively, have been chosen as top sand blanket materials. Also, for each sand blanket material, three different stone column materials (S, SS and ES-I) have been used to study the variation in time-dependent SCR and SCR$_p$. Figure 12 shows the variation in SCR with time for different stone column material properties. A similar pattern of SCR with time has also been observed here as discussed previously.

Figure 13 shows the variation in SCR$_P$ with top blanket materials properties for different column materials. SCR$_P$ reduces linearly as angle of internal friction of top blanket material increases. The stiffer top blanket helps in distributing the load coming to the top of stone column and surrounding soil more uniformly, which results a decrease in the peak SCR of the composite system. The observed reduction was found to be constant for all column materials. From the observed test results, it is suggested that the use of well-graded top blanket layer with adequate thickness will reduce the stresses developed near column surface, facilitate pore water dissipation and improve the performance of treated ground. Thickness of the sand blanket shows more pronounced effects on the SCR and SCR$_P$ when compared
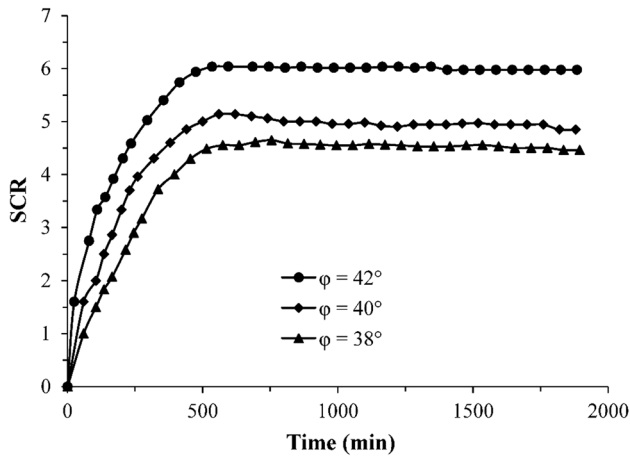

Fig. 10 Variation in SCR with time having 150 mm top blanket thickness for different column materials ($A_r = 17\%$)

Fig. 12 Variation in SCR with time for 300-mm-thick SS as top blanket layer with different column materials ($A_r = 17\%$, $\varphi_{stone\ column} = 38°$)
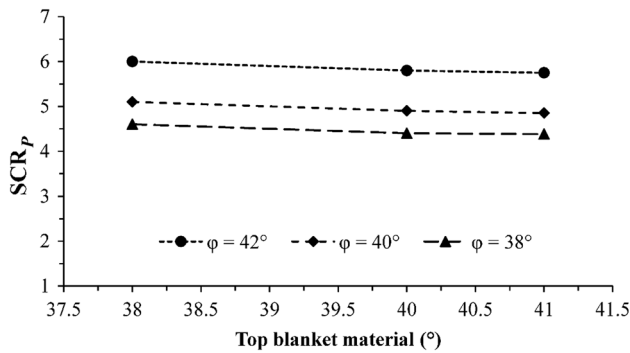

Fig. 13 Variation in SCR_P for different column materials and blanket materials

with material properties as is evident from the slope of the graphs.

Effect of surrounding soil strength

In this series of test, effect of undrained shear strength of the surrounding soil on the time-dependent SCR and SCR_P has been evaluated. In this series of test, area replacement ratio, sand blanket properties, thickness and applied stress level are kept as 17%, 38°, 150 mm and 120 kPa, respectively. S has been used as stone column material. Undrained shear strength of the surrounding soil has been changed in the range of 15–45 kPa. Figure 14 shows the variation in SCR_P with undrained shear strength of surrounding soil. The results show that SCR_P reduces linearly with increase in the undrained shear strength of surrounding soil. The relative stiffness of the stone column and surrounding soil reduces with increase in the undrained shear strength of surrounding soil. As the time-dependent SCR and SCR_P depend on the relative stiffness of stone column and surrounding soil, an
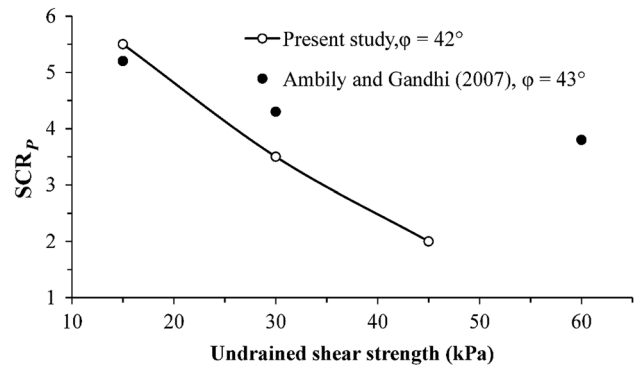

Fig. 14 Variation in SCR_P with initial undrained shear strength of surrounding soil ($A_r = 17\%$)

increase in the undrained shear strength of the surrounding soil decreases the SCR_P. The findings of the present study have also been compared with the experimental results of Ambily et al. [1]. A similar trend has been observed from both the studies.

Discussions and conclusions

The present work describe details of the experiments conducted on unit cell to understand the factors affecting the time-dependent and peak SCR of soft soil reinforced with stone column through surface loading conditions. The present study uses unit cell idealization to model single-column behaviour within an infinite group of stone columns in the field. The unit cell offers infinite stiffness in radial direction, thereby preventing any radial deformation of it, which may not be the realistic simulations of the field conditions due to finite stiffness in radial direction. Due to this, the settlement and SCR may be under- and overestimated in the unit cell idealization when compared with the field conditions. Also, behaviour and stress conditions of the edge columns in an infinite group of stone columns are significantly different from the middle or any other column. The unit cell fails to realistically idealize the behaviour of stone columns situated at the edge of a group. The findings of the present study are not applicable to the edge column or stone column group with limited number of stone columns. To measure the SCR, earth pressure cells are used. Area replacement ratio and material properties of stone column, top sand blanket thickness and its material properties, surrounding soil strength on the estimation of time-dependent SCR and peak SCR of the composite system have been evaluated. The following conclusions may be drawn from the results obtained for the material properties and parameter used in the present study.

1. Stress concentration ratio of the stone column-improved composite system varies nonlinearly with the application of surcharge load. Initially, SCR increases rapidly with time after application of load and then becomes constant and reaches steady-state stage. A similar time-dependent variation in SCR is observed for the different parameters tested of the composite system.

2. Area replacement ratio influences SCR of the stone column-improved composite system. Peak SCR is observed to increase with increase in the area replacement ratio of the stone column. The observed values of peak SCR range from 5.1 to 6.2 when area replacement ratio changes from 11.6 to 22.6%, respectively.

3. Peak SCR increases with increase in angle of internal friction of column material. From experimental results, the peak SCR increases from 4.2 to 5.5 when angle of internal friction of stone column material changes from 38° to 42°. Also, the stone column material properties show dominating influence on the peak SCR over the area replacement ratio of stone column.

4. Thickness and material properties of the top blanket significantly influence the peak and time-dependent SCR of the composite system. Peak SCR decreases with the increase in thickness and angle of internal friction of sand blanket material. However, thickness of the top sand blanket shows a significant influence on the peak SCR over the material properties of the top blanket.

5. The undrained shear strength of surrounding soil plays a major role in stress concentration ratio. Relative stiffness of the stone column and surrounding soil decreases with the increase in undrained shear strength of the surrounding soil, which results in a decrease in the peak SCR of the composite system.

6. The results show that the peak SCR is significantly influenced by the stone column material properties, top sand blanket thickness and surrounding soil strength among the various parameters experimented in the present study.

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