Research Paper

Behavior of Sand Compaction Columns Installed in Cohesionless Deposits

N. Aarthi*

Abstract: A critical appraisal of the reviewed literature revealed that there are very limited studies available on the strength characteristics focusing on the load-settlement behavior of sand compaction columns (SCCs) when installed in cohesionless deposits. The method, though contemporary to the reputed stone column technique, is not yet studied rigorously in the available past studies, more precisely on the load-bearing characteristics when compared to the latter. Therefore the present study focuses on studying the behavior of multiple column composite foundation supported by sand compaction columns installed in loose to medium dense sands on a lab-scale numerical model. The study is carried out using commercially available finite element (FE) code 3D PLAXIS. Spacing to diameter ratio (S/D) ranging from 1.5 to 3.5 and initial relative density (RD) from 30 to 60% was adopted to study the changes in the load-settlement behavior of the improved deposit. Extending the FE model to further parametric study, the effect of angle of internal friction of the column sand and diameter of the column on the bearing capacity and settlement characteristics were analysed with and without normalization. From the results obtained, it is found that, for the considered FE model, the improved deposit with 3D spacing between the SCCs behaves distinctly different from all other cases analyzed.

Keywords: sand compaction column, finite element analysis, parametric study, angle of internal friction, diameter of the column

Introduction

Invented in 1956, the sand compaction column (SCC) ground improvement technique is one of the most preferred ground modification methods in Japan to improve loose cohesionless deposits and soft grounds (Terashi and Katagiri, 2015). Unlike other treatment methods like dynamic compaction, blasting, reinforcement by fibers, metal strips, and fabrics (Geosynthetics), and soil nailing that are often adopted to treat the loose cohesionless deposits, installation of sand compaction columns (SCCs) have differently unique working strategies when installed in clay and sandy grounds. In clay ground, it majorly functions as a deep replacement technique and is used for a maximum depth of 70 m (Han, 2015). In cohesionless deposits, they function as Vibro-compaction, where the driving of the casing into the natural ground provides adequate vibration needed to densify the soil around the casing and displaces laterally to accommodate the sand compaction column (SCC) newly formed.

From the past studies available, it is noticed that the performance of SCC improved clayey deposits in terms of strength improvement is reported vastly by many researchers. A few of them are outlined here (Kim and Lee, 2005; Juneja *et al*., 2011; Al-waily, 2012; He *et al*., 2018). A large number of laboratory and field tests have been conducted to quantify the applicability of this ground improvement technique to improve the behavior of soft ground. A few of them are (Hughes *et al*., 1975; Madhav, 1982; Charles and Watts, 1983; Kimura *et al*., 1985; Bergado and Lam, 1987; Bergado *et al*., 1988; Leung and Tan, 1993; Alamgir *et al*., 1996). Despite the vast documentation carried out on the effectiveness of the technique in improving the soft soils, studies focusing on the strength characteristics of SCC installed in cohesionless deposits are found to be very limited (e.g. Samanta *et al*., 2010; Ashwathy *et al*., 2013; Aarthi *et al*., 2019).

Among the above-mentioned studies, Samanta *et al.* (2010) and Aarthi *et al.* (2019) reported the behavior of SCCs by carrying out laboratory studies for a particular diameter of SCC installed in the sandbed prepared in a confined dimension. Samanta *et al.* (2010) discussed the performance of SCC improved sand deposit by analyzing the effect of parameters namely, the number of columns under loading and the magnitude of improvement attained leading to a shortfall of information on other vital parameters like SCC material (sand or mixture of sand and aggregate), angle of internal friction of the SCC, diameter of the column, modulus of

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the intervening soil, etc. on the load-bearing characteristics of the improved sandbed. Aarthi *et al.* (2019) reported the strength characteristics in terms of the pressure-settlement response of SCC considering the effect of parameters namely, spacing (S), initial relative density (RD) of the sandbed, and the number of columns only. On the other hand, work reported by Ashwathy *et al.* (2013) is a field case study where the improvement effect was evaluated by recording the standard penetration test values, i.e., SPT-N values, and no particular response was monitored directly other than an indirect estimation of treatment, that is reflected by SPT-N values.

Though the above studies provide a basic understanding of the behavior of SCC in sand deposits, the effect of crucial parameters like the internal angle of friction and diameter of the column in altering the load-bearing and settlement characteristics is not yet addressed. Added to that, the studies were carried out in an experimental setup in which feasibilities of implementing different SCC diameters to study their effect, is a highly demanding work since it requires designing and fabrication of multiple casings of different geometric conditions. Also, studying the effect of change in the angle of internal friction of the SCC in a laboratory-scale investigation is a highly strenuous effort to maintain the angle throughout the depth of the column. The usage of finite element (FE) tools overtakes the laboratory studies in such scenarios, providing the greatest advantage to monitor these responses of the SCC improved sandbed more precisely, in an extensive manner.

Therefore, the present study is addressed aimed at intending this research gap detailed above, to study the effect of internal angle of friction of the column sand and the diameter of the SCC in loose to medium dense sandbed in a FE model. The numerical simulations are performed to carry out a comprehensive study on the response of multiple column composite foundation (MCCF) resting on an SCC improved sandbed. It is further accompanied by the effect of the change in the parameters in affecting the load-carrying capacity and compressibility characteristics in terms of pressure-settlement response. Separate sections detailing the parametric study with and without normalization are presented. The failure mode experienced by the foundation resting on the SCC improved sandbed is also outlined as part of the results and discussion followed by the conclusions.

Experimental Study

Laboratory plate load tests were initially carried out as part of the experimental investigations to analyze the behavior of the sand compaction column treated sandy ground. The dimensions are limited to 1 × 1 × 1 m. A sandbed of known initial relative density is initially formed through the sand-raining technique in the test tank and then the SCCs are installed as per the desired configurations. Static compression load tests were conducted for various combinations of initial relative densities of the sandbed and pile spacing. A detailed version of this experimental work can be referred to in Aarthi *et al.* (2019). As mentioned in the latter part of the introduction section, to overcome certain practical implementation difficulties experienced in the experimental work, the present study of analyzing the behavior of SCCs in sands numerically with a finite element software is envisioned. The numerical modeling, the FE results presented and discussed herein this paper, and the corresponding conclusions drawn are based purely on numerical simulations only, with no relevance to the above article cited. The only similarity is the dimension of the soil domain studied (1 × 1 × 1 m).

Numerical Modeling

The numerical simulation presented in this paper is intended to replicate the laboratory experimental setup dimension reported by Aarthi *et al.* (2019). Therefore, the lab-scale FE model created for the present study is referred to hereafter as just 'FE model' throughout this paper. The FE model of the SCC improved sandbed was simulated using the PLAXIS 3D software. The soil domain was created initially by assigning the geometrical dimensions of the test tank as in the laboratory and the soil stratum is introduced by using the borehole option, with the input properties of the loose sand. The sandy soil used to form the sandbed and the compaction column falls under the category of poorly graded sand (SP) as tested and classified in accordance with ASTM D422-63 (2007) and ASTM D2487-11 (2011a). Mohr-Coulomb model was chosen to represent the behavior of sandbed and the SCC as it provides a first-order approximation of the model, incorporating a minimum number of parameters. The sandbed considered for the study is of dimension 1000 × 1000 × 850 mm as observed from Figures 1 and 2. As far as the boundary conditions are concerned, the top layer is set to be free to move in all directions and the bottom boundary is fixed in all directions. SCC of 60 mm diameter (D) and 500 mm depth are installed throughout the test tank for varied SCC configurations from 1.5 to 3.5D. The installation of the piles can be modeled as an expanding cavity of known diameter (Ammari and Clarke, 2018). This method involves applying volumetric strain to the sandbed, to model the densification achieved by the displacement of sand particles while accommodating the sand compaction column, throughout the test tank. This method results in the heaving of sand surrounding the columns because of expansion. However, while obtaining the pressure-settlement plot of the SCC improved sandbed in the finite element method (FEM), this heaving can be neglected by resetting the displacements to zero in the calculation phase of the program. This method of applying positive volumetric strain is employed in the current simulation, which works on the principle of cavity expansion.

The modeling of the sand compaction column was carried out by employing a predefined cylinder option available in the software. The cylindrical volume of elements was created throughout the soil domain at the respective locations of the SCCs and is imparted with the soil properties of the SCC. The diameter of the footing was estimated appropriately in such a way that it covers the effective diameter (d_e) i.e., tributary area of the columns chosen for the testing. Plate elements were chosen to model the foundation. Since the entire study was carried out in an unsaturated condition, and the geomaterial understudy is sand, the drained condition was adequately chosen to define the drainage characteristics of the improved soil

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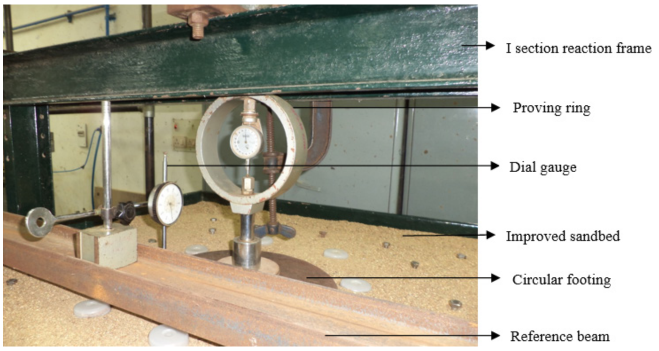

Figure 1. Laboratory test setup for plate load test

medium throughout the further analysis. Another vital aspect that decides the response of the system is the mesh discretization where it is to note that each and every model has its inherent set of convergence limits. For the present finite element analysis (FEA), the soil volume of the sandbed and the SCC were discretized into medium meshing with a relative element size factor (r_e) value of 1. The sand compaction column group with three numbers of columns along with their tributary area is collectively termed as the Multiple Column Composite Foundation (MCCF) as recommended by Han (2015). MCCF is replicated by loading 3 numbers of columns at the center of the FE soil domain created as shown in Figure 2. The foundation may be surrounded by a minimum of one or two layers of columns since they are essential to provide the much-needed confinement to the columns under loading against failure and it also adequately represents the field situation. Static compression loads on the MCCF is simulated by subjecting the foundation to undergo a predefined displacement value of 80 mm.

Validation

The input parameters used for the FE study are listed in Table 1. Unit weight is obtained by back-calculation of RD from the laboratory test, which is measured after installation of the column, with the help of a self-weight penetrometer. The angle of internal friction (φ) for each initial RD is obtained by a direct shear test conducted as per ASTM D3080 / D3080M-11 (ASTM 2011b). Poisson's ratio is reported from typical values suggested by Bowles (1988). Dilation angle (ψ) is estimated by Equation 1, as suggested by (Bolton, 1986).

$$\psi = \phi - 30° \quad (1)$$

$$E = 7000 \times (\sqrt{N}) \quad (2)$$

Where E is Young's Modulus is obtained by an empirical equation reported in Bowles (1988), which involves back calculating SPT-N value for the improved relative density after treatment. R_{inter} is the interface factor between the foundation and the SCC improved sandbed. This defines the magnitude of friction transferred at the interface to induce the mobilization of shear strength. A common range of 0.4 to 0.9 is often used in soil-structure interaction problems Damians *et al.* (2015).

Table 1. Input properties for the FE model

Properties	Symbol	Tank sand	Column sand
Density, kN/m^3	γ	16.5	17.3
Young's Modulus, MPa	E	36	45
Poisson's Ratio	υ	0.25	0.3
Angle of Internal Friction, Dilatancy angle, °	φ, ψ	33,3	39,9
Interface factor	R_{inter}	0.9	0.9

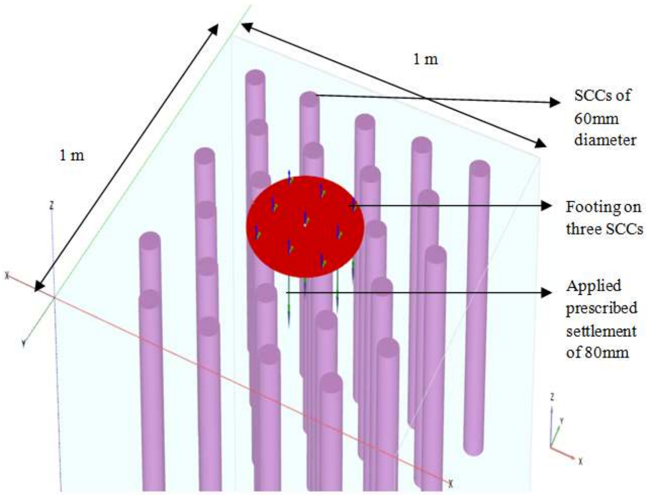

Figure 2. Close view of footing under prescribed displacement of 80mm

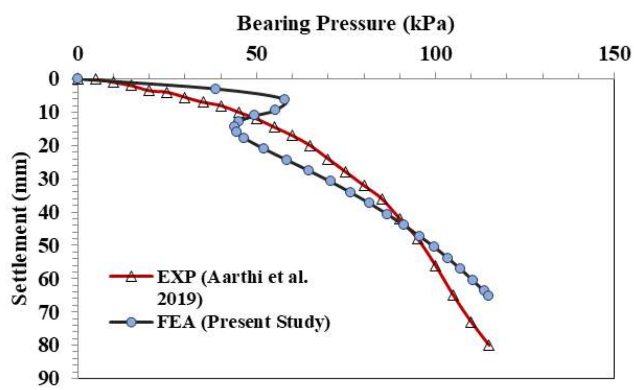

Figure 3. Response of SCC improved sandbed subjected to static compression loading: Laboratory and Numerical output (Initial R.D = 40%, S = 2.5*D*)

The model thus simulated is validated against the experimental work in terms of pressure-settlement response as shown in Figure 3. The results are compared and are found to match reasonably well with a negligible amount of underestimation in FE output (less than 12% percent) in comparison to the laboratory result as observed from Figure 3. The ultimate bearing capacity (UBC) of the SCC treated sandbed for the FE model is obtained by adopting the double-tangent method (Aarthi *et al*., 2019). The UBC is also commonly referred to

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as failure stress or the limiting axial stress or axial capacity of the treated ground improved by columnar inclusions like sand compaction columns and stone columns (Ambily and Gandhi, 2007). It could be observed that the FE result from the numerical simulation doesn't reach a settlement value of 80 mm since it has undergone failure before reaching the predefined displacement value fixed for the present FE model. Unlike experimental investigation, the FEA helps in analyzing the mode of failure that the improved sandbed could undergo when subjected to compression loading.

Results & Discussion

Parametric study without normalization

The study is aimed at observing the behavior of SCC improved sandbed in terms of pressure-settlement characteristics of the following: i) Range of spacing adopted between the columns (1.5, 2, 2.5, 3, and 3.5*D*) and the initial RDs of the sandbed (30, 40, 50, and 60%), ii) angle of internal friction of the SCC and, iii) diameter of the column (SCC). The present section explains the results of FE simulations carried out as listed above in sequential order.

Behavior of multiple column composite foundation for varying spacing and initial RD

The area replacement ratios (ARRs) corresponding to the adopted spacing range 1.5 to 3.5*D* is 5 to 26.8%. In order to understand the effect of column inclusion in the system, initially, four tests (one in each initial RD) were conducted without installing any columns in the sandbed. To analyze the behavior of SCC improved sandbed, in total, 20 FE outputs were obtained from the combinations of the spacing (1.5 to 3.5D) and initial RD (30 to 60%) range. The primary purpose of adopting any ground improvement technique is to improve the native deposit that is present in loose condition. Enhancing their load-carrying characteristics and understanding their behavior under loading gathers significance plausibly for an effective treatment. Therefore, the case with initial RD 30% is presented in Figure 4, illustrating the effect of varied spacing range on the pressure-settlement behavior of MCCF. It is notable from the trend of the plot obtained from the FE results that, the sandbed has undergone densification as it exhibits a linear trend followed by a non-linear trend analogous to that of the behavior reported for cohesionless soils in dense condition (BIS 1888: 1992).

Invariable of the spacing adopted between the SCCs, the FE pressure-settlement response of the SCC improved sandbed shows a profound failure peak in its trend. From Figure 4 it can be inferred that the MCCF tested on the SCC improved sandbed for 3*D* spacing behaves distinctly in comparison to all other cases studied. The plot is linear and the transition from the linear to non-linear portion with a change in slope happens at a larger value of the settlement. And it is noticed that this distinct behavior of the 3*D* MCCF case occurred in all the FE outputs observed irrespective of the initial RDs considered. This behavior of the 3*D* case has to be studied further in detail in future research works. Added to that, is the observance that only at this 3*D* spacing, the MCCF reached

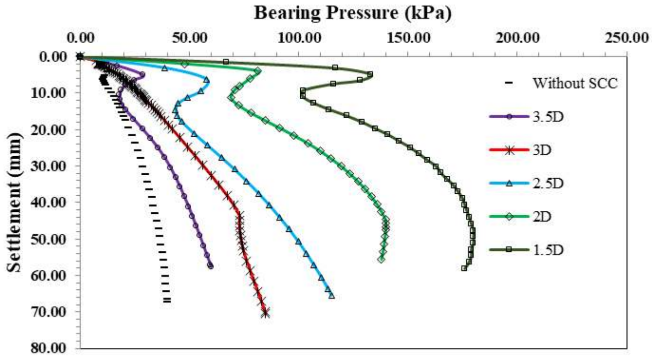

Figure 4. Pressure- Settlement Plot for the MCCF in SCC improved sandbed for FE model (30% Initial R.D)

a maximum of 70 mm before attaining failure, a value very close to predefined displacement value of 80 mm set manually. The MCCF in all other cases and the untreated sandbed failed before attaining 70 mm of settlement.

Increment in load-carrying capacity corresponding to S/D ratio 1.5, is found to be 35% higher when the initial RD is increased from 30% to 60%. Likewise, for S/D ratio 2 it is 41%, 2.5 is 62%, 3 is 59% and 3.5 is 82%. Therefore, it is clearly evident that the installation of sand compaction columns yields the best results for the least area replacement ratio adopted (i.e. 3.5*D* case). The values of percentage difference in the increment of load-carrying capacity obtained for smaller spacing (1.5, 2*D*) and higher relative densities (50, 60%) are found to be lesser when compared to the larger spacing (3, 3.5*D*) and smaller initial RDs. Therefore it can be stated that the improvement effect is much pronounced in larger spacing and smaller values of initial RDs. On the other hand, for the present FE model the maximum load-carrying capacity is achieved for the case of 1.5*D* spacing with 60 % initial RD.

Figure 5 shows the variation of UBC (axial capacity) based on FE test results for all the initial RDs considered, along with the different spacing adopted. The figure shows that the limiting axial stress increases linearly with an increase in initial RD for a given spacing. The percentage difference in increment in load-carrying capacity for different spacing and the initial RDs adopted for the MCCF is presented in Figure 6. The percentage difference in increment is obtained with respect to the ultimate bearing capacity of the unimproved sandbed to the improved sandbed at respective initial RDs. From Figure 6 it can be clearly inferred that the percentage difference in increment is linear, with a negligible degree of non-linearity in higher initial RD cases. Also, it is noted that at 2.5*D* spacing, irrespective of the initial RDs adopted, the trend of the curves shows an appreciable increment in the load-carrying capacity of the MCCF.

Effect of internal friction angle of columns

The effect of the internal angle of friction on the MCCF in SCC improved sandbed was studied by varying the φ value of the SCC alone, while the φ value of the surrounding sandbed

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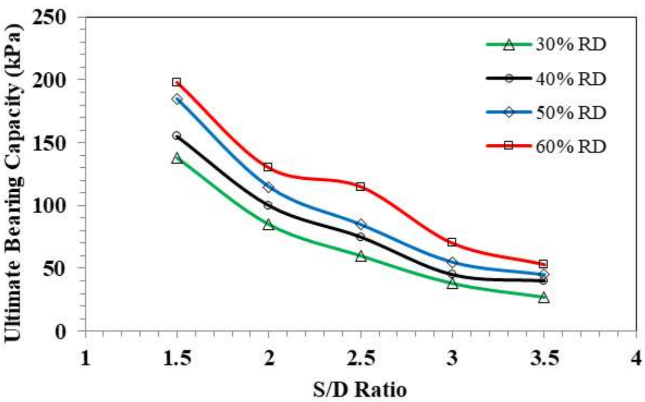

Figure 5. Variation of Limiting axial stresses based on S/D ratio

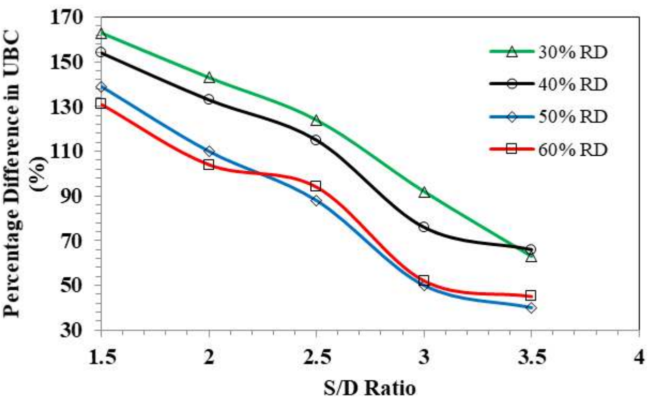

Figure 6. Percentage difference in increment of axial capacity of MCCF with respect to untreated sandbed

is kept constant. The diameter of the column (D) is kept constant at 60 mm for the FE simulations carried out in this section. MCCF of S/D ratio 2.5 was subjected to this parametric study, where the angle of internal friction is changed (39, 40, and 41°). The reasoning for the considered φ value range as mentioned above is attributed to the following reasons: The internal angle of friction of the sand compaction column is found to be 39 degrees (as obtained from the direct shear test) pertaining to an initial RD of 73%. Thus for any case involving further possible parametric variation, the column is expected to have more strength than the present initial RD of 73%. Therefore a range of angles of internal friction greater than 39° is chosen. On the other hand, sand particles may reach a maximum value of friction angle 43°, and anything above this value is usually observed in columns made of sand and aggregate mixture or gravel columns that are normally adopted in construction practice. The effect of friction angle and initial RD on the load-carrying capacity of the MCCF is shown in Figure 7.

When the angle of internal friction increases, a steady increment in the load-carrying capacity of the multiple column composite foundation is observed, this is clearly evident from Figure 7. For smaller initial RDs the increment in ultimate bearing capacity of the foundation linearly increases

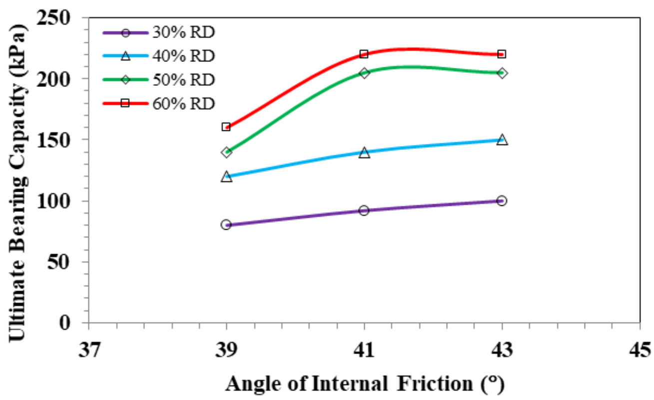

Figure 7. Effect of friction angle and initial RD on axial capacity of MCCF

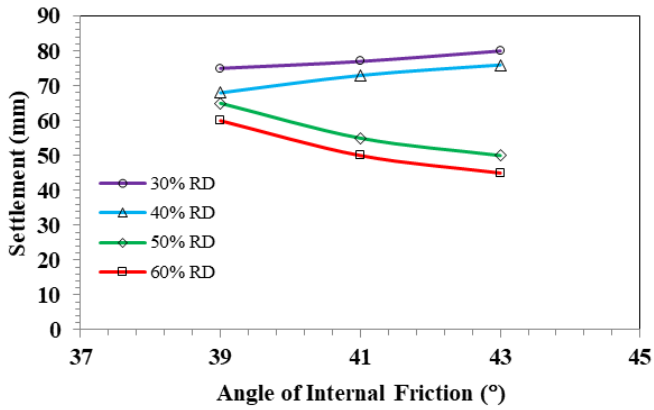

Figure 8. Effect of friction angle and initial RD on the settlement of MCCF

with increment in the angle of internal friction. For higher initial RDs, the increment in UBC is found to be non-linear, with a distinct peak occurring at 41°. This profound behavior showing a peak increment is of significance and has to be studied further comprehensively for possibilities of adopting in the actual practice of the SCC improvement technique. From Figure 7, it can also be inferred that the increment in UBC of the improved sandbed increases with an increase in φ value. On the other hand, the magnitude of UBC increment is found to be greater for higher initial RDs (50 and 60%) for a constant value of angle of internal friction. Therefore, it can be stated that the initial RD of the natural ground predominates the behavior of MCCF in SCC improved sandbed when compared to the angle of internal friction of the SCCs that are installed for reinforcing the native deposits.

Figure 8 depicts the effect of the internal angle of friction on settlement characteristics of SCC improved sandbed. The settlement of the foundation (MCCF) decreases for higher initial RDs, with an increase in friction angle. For smaller initial RDs, the settlement increases upon increasing the friction angle from 39 to 43°. This is attributed to the fact that loose sand deposits undergo compression for increasing stress levels and dense sand samples tend to undergo dilation when subjected to a higher pressure level, which is a well-established behavior of sandy soils when tested in a triaxial apparatus. Though the present study doesn't maintain a perfect confining pressure as in the triaxial testing, the confining pressure offered to the soil particle at higher initial RDs by the compression loading is expected to be adequate enough to mobilize the shear strength to undergo dilation by the SCC improved sandbed, which eventually results in evidently notable settlement value. These settlement characteristics of the MCCF of the SCC improved sandbed provide valuable information on the behavior of improved sandy grounds subjected to static compression loading. However, this response of settlement characteristics (undergoing dilation) for higher initial RDs of the sandbed, for higher friction angles of SCC can be subjected to further rigorous study in field-scale models of FE, before adopting in field execution.

Effect of diameter of column

This section of the study is intended to address the drawback of studying the effect of the diameter of SCCs in a laboratory experiment since it will require special pile driving equipment (casing) of different diameters, resulting in a cumbersome effort. Employing FE facilitates this drawback with ease by effectively performing numerous simulations taking into account this parametric influence on the MCCF's characteristics. MCCF resting on columns installed with S/D ratios 2, 2.5, and 3 were subjected to study the effect of the diameter of the column (60, 70, and 80 mm). The reason behind choosing larger diameter of columns is deliberately to address the field situation, where often larger diameters of SCCs are used for practice. The effect of the diameter of columns on the load-carrying capacity of MCCF is shown in Figure 9. The experimental data from the literature (Aarthi *et al.* 2019) is given in Figure 9 only for validation purpose and to observe the difference in the load-carrying capacity between the experimental results and the FE outputs. The tests are carried out for a constant initial RD of 40%.

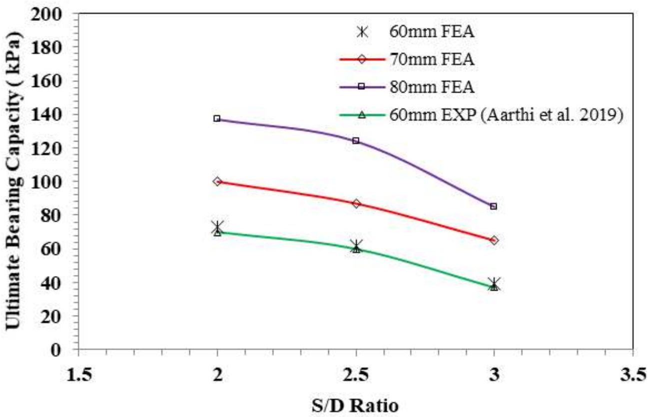

Figure 9. Effect of the diameter of the column on axial capacity of MCCF

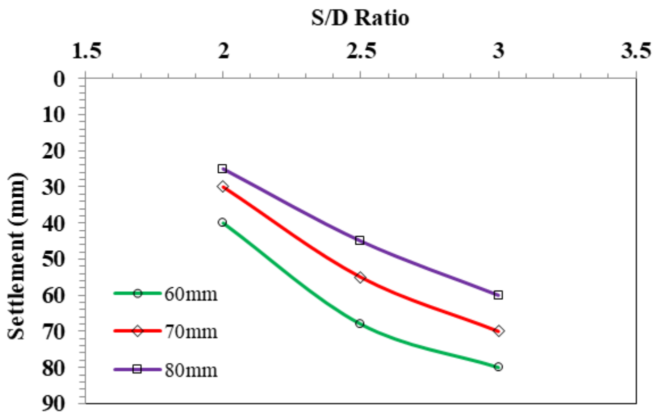

Figure 10. Effect of the diameter of the column on the settlement of MCCF

It could be inferred from Figure 9 that the present FE outputs match reasonably well in estimating the UBC of the SCC improved sandbed for the case of 60 mm diameter of the SCCs employed for the considered spacing range 2 to 3*D*. It is evident from the figure that the UBC of the SCC improved sandbed increases when the diameter of the column is increased from 60 to 80 mm. On the other hand, it is to note that irrespective of the diameters used for the study when the spacing is increased from 2 to 3*D* the ultimate bearing capacity decreased to a notable extent. Therefore, it can be stated that the spacing predominant the diameter of the sand compaction column in altering the behavior of the load-carrying capacity of MCCF, resting on an SCC improved sandbed. On an overall note, the trend appears to be linear for smaller values of the diameter of the columns used, i.e., for 60 and 70 mm, whereas, for larger diameters of the column, there lays a marginal non-linearity when the spacing is increased from 2 to 3*D*.

Figure 10 illustrates the effect of the diameter of the SCC on the settlement characteristics of the MCCF when placed on the SCC improved sandbed for an initial RD of 40%. Only the FE outputs are considered for analyzing the settlement characteristics of the SCC improved sandbed. Larger the diameter, the settlement of the MCCF is found to be less as inferred from Figure 10. However, it is found that when the spacing is increased from 2 to 3*D*, independent of the diameter of the SCCs used, the settlement tends to increase. Thereby, it can be proposed that spacing predominate the diameter of the SCCs in altering both the load-carrying and settlement characteristics of the MCCF. Columns of larger diameter (80 mm) behave linearly upon increasing the spacing whereas there is a profound peak in non-linearity in the settlement behavior of the improved sandbed when the smaller diameter columns (60 mm) are used in the analysis.

Both the effects of the internal angle of friction and the diameter of the SCCs in influencing the load-bearing and compressibility characteristics are very crucial and essential while designing ground improvement techniques involving columnar inclusions like stone columns and sand compaction piles. Therefore these studies carried out in the FE model so

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far in the present paper can be analyzed further for field-scale dimensions also. An attempt has been made in the following sections to normalize the parameters such that it can result in a dimensionless coefficient that can apply to field dimensions.

Parametric study with normalization

The factors normalized and grouped to establish a dimensionless framework are:

- Spacing and diameter of the SCCs.
- In-situ density of the sand strata – post improvement, and
- Width or diameter of the foundation.

The dimensionless numbers that are grouped together in the framework are:

1. S/D ratio => Spacing of the SCC (m) / Diameter of the SCC (m).
2. Bearing capacity factor, $q_u/ (\gamma * d) \Rightarrow$ Ultimate bearing capacity / (In-situ unit weight of the improved deposit * diameter of the footing, i.e., loaded area).
3. s/ d ratio => settlement of the footing (s) / diameter of the footing (d) in mm.

In the above, q_u – in terms of kPa or kN/m^2, γ – in terms of kN/m^3, d – Diameter of the footing in m. The framework gives the ultimate bearing capacity of the SCP treated sand deposit, for any desired value of the spacing between the SCPs, the diameter of the SCPs, size of the footing, and for the specified target unit weight required for the intended application and the given site conditions.

Behavior of multiple column composite foundation for varying spacing and initial RD

A framework developed from the results of the FE simulation of the laboratory SCC model is illustrated in Figure 11. The figure will give a complete picture of the UBC or axial capacity attained from the FE model results. For the pre-selected S/D ratio of the SCC technique, size of the footing, and the required target unit weight to be achieved for the deposit, the framework can be used to obtain the bearing capacity factor. Using the bearing capacity factor, the ultimate bearing capacity of the improved deposit can be evaluated based on the range of the initial RD (30 to 60%) of the sand deposits.

It is to note that the trend of curves comparing Figures 5 and 11 is found to be identical, i.e., before and after normalization. The reason behind lies in the fact that with the x-axis being the same in both the Figures, only the y-axis is normalized, whose denominators vary only in terms of the unit weight of the sand, and the height of the SCC being constant at 500 mm. A change in the trends is expected to occur when the height or depth of the SCC that shall be studied varies.

Effect of internal friction angle of columns

The effect of the internal angle of friction of sand compaction columns is studied in this section with the normalized parameters. Figure 12 depicts the dimensionless framework based on the behavior of the SCC improved sandbed. On comparing Figures 7 and 12, it can be inferred that the trends are identical. This is because the y-axis represents the normalized dimensionless

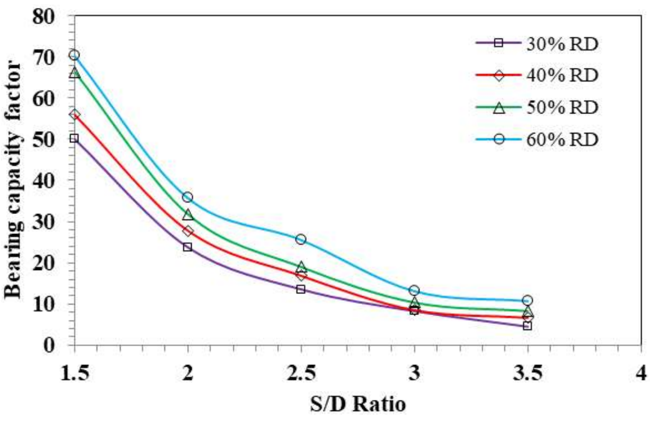

Figure 11. Numerical variation of Bearing Capacity factors with S/D Ratio for the axial capacity of MCCF

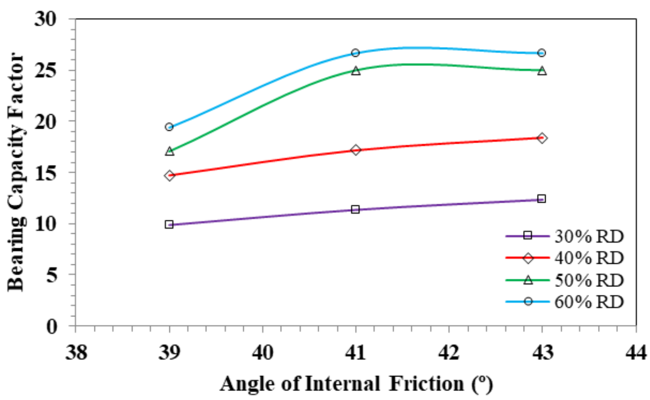

Figure 12. Effect of friction angle and initial RD on the bearing capacity factor of MCCF

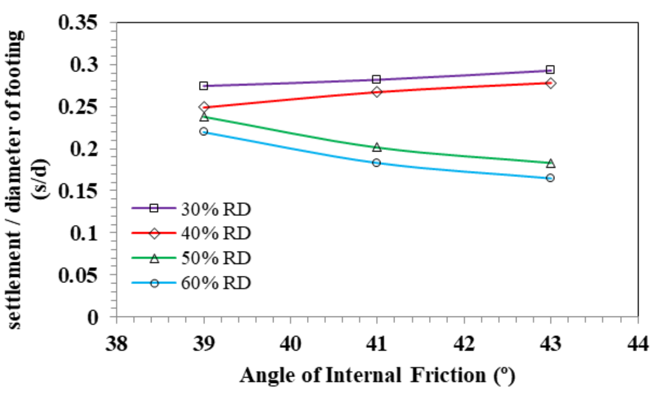

Figure 13. Effect of friction angle and initial RD on the s/ d ratio (settlement/ diameter of the footing) of MCCF

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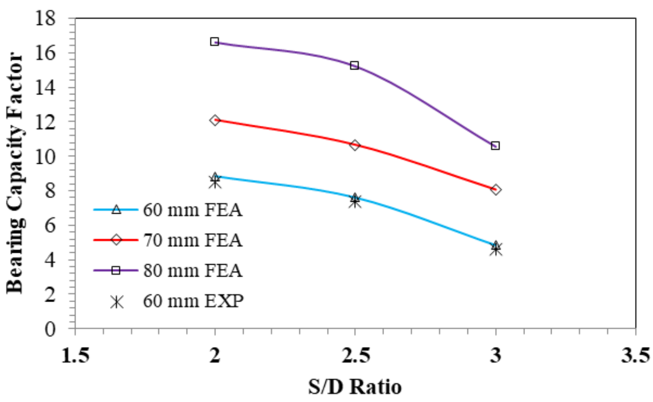

Figure 14. Effect of diameter of SCC and S/D ratio (spacing / diameter of SCC) on the bearing capacity factor of MCCF

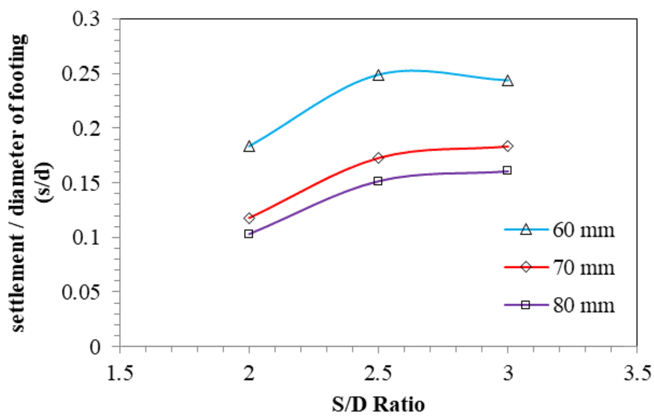

Figure 15. Effect of diameter of SCC and S/D ratio (spacing / diameter of SCC) on the s/ d ratio (settlement/ diameter of the footing) of MCCF

term Bearing capacity factor related to the angle of internal friction of the sand, which is an independent parameter altogether.

Figure 13 is purely dimensionless and can be related to a real-field scenario with ease. A different trend is expected if the height of the columns is varied. Therefore, it can be stated that the behavior of the SCC's can be presented adequately with normalized parameters for a given fixed depth of the column, even otherwise this normalization could project the changes directly in Figures 12 and 13.

Effect of diameter of column

Similar to the previous sub-sections, on a comparison between Figures 9 and 14, one can infer that the trends of the curves remain unchanged despite normalization. And the reasons attributed are found to be the same SCC depth and smaller variations in the unit weight of the sands considered in the present parametric range.

Consequences of a lab-scale test to a field-scale scenario

Often a lab-scale has this major consequence to a field-scale scenario. The Scale Effect. The pressure-settlement response and the type of failure mechanism exerted by the footing resting on an SCC improved cohesionless deposit may undergo variation when the dimensions of the components like the volume of area to be treated, depth, or length of the SCC, width or diameter of the footing differs. Therefore an attempt has been made in the present study to minimize the scale-effects of the results presented as an outcome of FE simulations of a smaller domain by introducing dimensionless coefficients. These dimensionless parameters can adequately represent the relation both quantitatively and qualitatively between the lab-scale FE output and a real-time application.

Observation of Failure Mechanism in FE model of SCC

Analyzing the development of the deformation pattern of the MCCF resting on SCC improved sandbed will provide an extensive foresee into the mode of shear failure experienced by the foundation. It is found from the available past literature that, studies pertaining to the deformation pattern of foundations resting on SCC groups installed in sand deposits are hardly any. Thus the present section analyzing the deformation characteristics of the SCC improved sandbed is expected to provide significant information for accelerating wide applicability of the technique in real-time projects. The failure undergone by the FE lab-scale SCC improved sandbed is observed to be a progressive shear failure undergoing continuous deformation. The failure wedge undergoes a deformation pattern similar to that of Terzaghi's theory as observed in Figure 16. The same type of failure wedge is observed for all the cases from 1.5 to 3.5*D* spacing for initial RDs varying from 30 to 60% as considered in the present study.

Figure 17 depicts the deformation with respect to only the longitudinal direction (*Z*-direction), referred to as U_z for SCC improved sandbed. It is noticed that the MCCF undergoes failure with a zone of heave around the periphery of the foundation. As seen from Figure 17, it is noted that the magnitude of heave occurred is 12 mm, pertaining to the case of 2.5*D* spacing between the SCCs. Upon varying the spacing and initial RDs of the sandbed to be treated, this magnitude of heave attained is found to vary over a range of 4 to 15 mm from the original level of the sandbed in the FE soil domain. It is also found that the magnitude of heave recorded is directly proportional to the initial RD of the sandbed, i.e. when higher initial RDs are employed for the sandbed, it resulted in a higher degree of heave after the failure of the MCCF. Figure 18 depicts the improved sandbed showing the lateral movement of soil particles accounting to the positive and negative U_x values as shown in the legend. It can be observed from the figure that the displacements in the horizontal direction (*X*-direction), referred to as U_x for SCC improved sandbed for 2.5*D* spacing with 60% initial RD recorded maximum positive value of 20 mm. The horizontal displacement of sand particles from the center of the foundation at coordinates (500, 500) towards the direction of the x-axis is described in positive U_x values.

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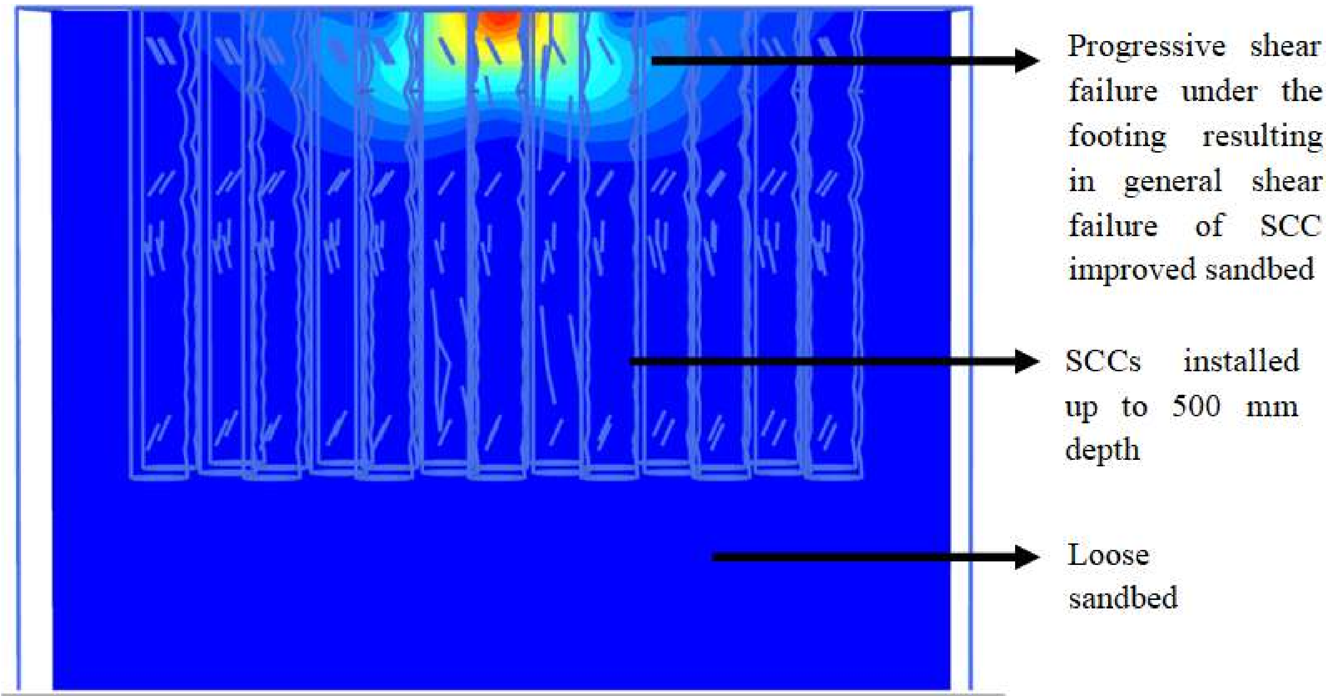

Figure 16. Total deformation pattern of the SCC improved sandbed for lab-scale FE model (initial RD = 60%, *S* = 2.5*D*)

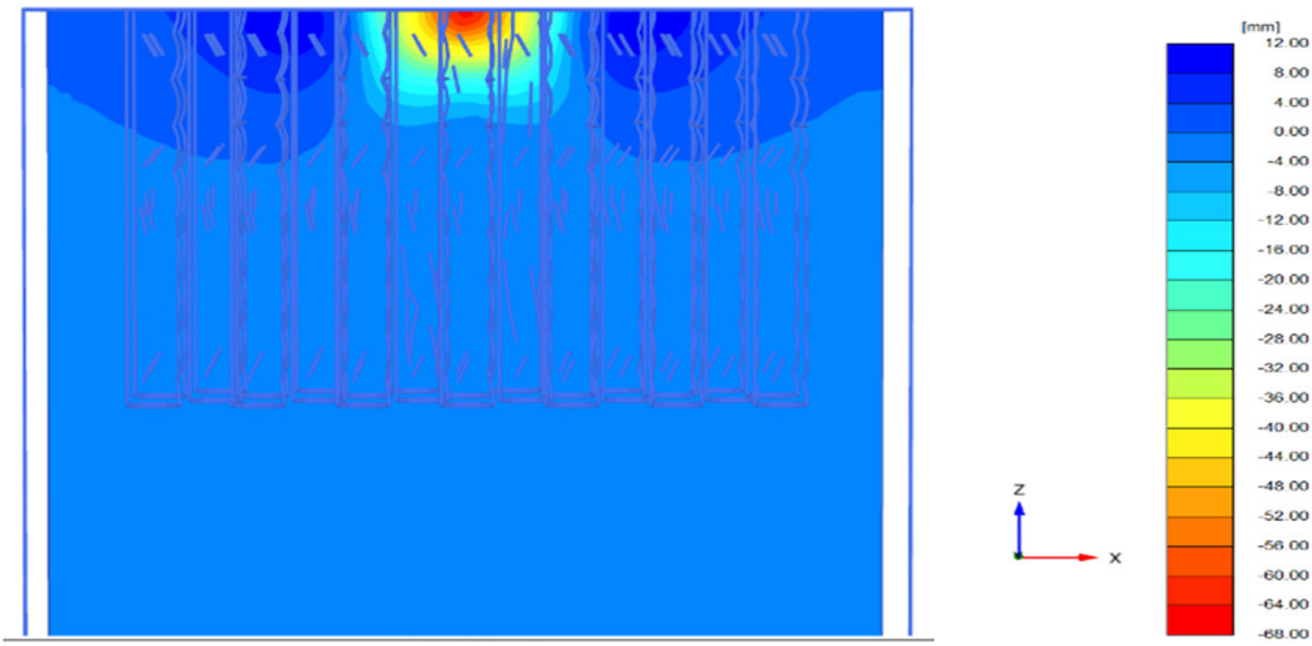

Figure 17. Deformation in the longitudinal (U_z) direction of SCC improved strata (initial RD = 60%, *S* = 2.5*D*)

The movement of the sand particles from the center of the MCCF towards the origin of the tank boundary is calculated in negative U_x values. It can be observed that both positive and negative U_x values are equal, which clearly depicts that the movement of the sand particles, or in other words, the deformation pattern is symmetrical from the center of the MCCF about *X*-direction. And this symmetrical pattern is observed in all the cases from 1.5 to 3.5*D* spacing for initial RDs from 30 to 60%. This information about the deformation pattern of SCC improved sandbed is expected to provide significant understanding while determining the extent of strain field occurrence (stress bulb) below the foundation.

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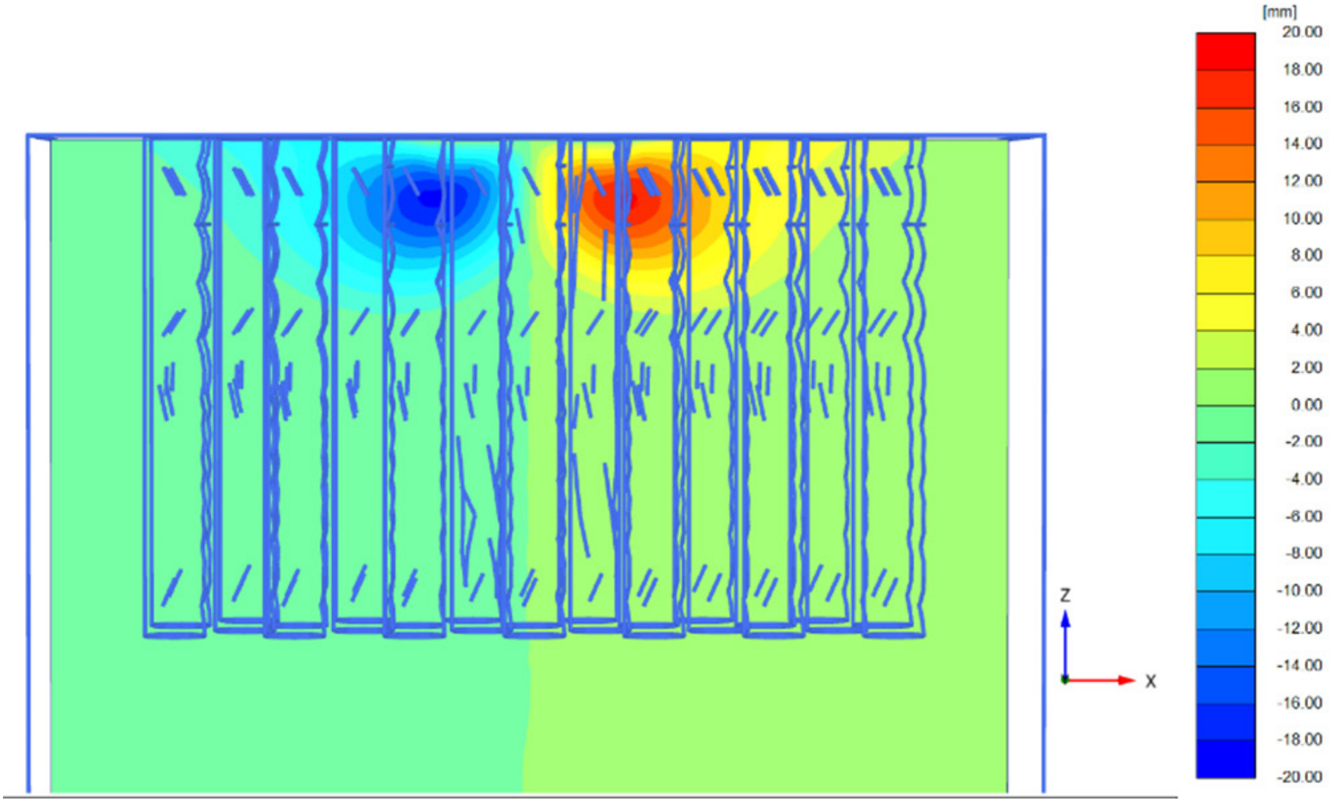

Figure 18. Deformation in the horizontal (U_x) direction of SCC improved strata (initial RD = 60%, S = 2.5*D*)

Conclusions

Numerical finite element simulations are carried out to analyze the behavior of sand compaction column (SCC) groups under static compression loading for a confined dimension of 1 × 1 × 1 m. The FE outputs are validated against experimental result available in the literature and are employed for further parametric study. The effect of the internal angle of friction and diameter of the SCC on the load-carrying and settlement characteristics of the SCC improved sandbed is discussed in detail with and without normalization. The deformation pattern and the failure mode experienced by the SCC improved sandbed are also investigated. The following conclusions are drawn from the study:

- FE models simulated provided a negligible underestimation of the axial capacity (less than 12%) of the SCC improved sandbed, in comparison to the existing literature with a reasonably good match.
- Multiple column composite foundation (MCCF) resting on SCC improved sandbed with 3*D* spacing holds a distinct behavior in terms of load-carrying capacity, undergoing plastic deformation only after 40 mm of settlement irrespective of the initial RDs of the sandbed.
- The magnitude of increment of ultimate bearing capacity is more than 20% for higher initial RDs (50 and 60%) for a given internal angle of friction, clearly representing the predominance of the parameter initial RD over friction angle.
- Dimensionless coefficients presented will aid in providing a direct estimation of the ultimate bearing capacity of the SCC improved cohesionless deposits, with few known parameters.
- The foundation is found to fail by progressive shear failure eventually resulting in a generalized shear failure with a definite failure wedge extending beyond the ground surface, resulting in a zone of heave surrounding the periphery of the foundation.

Notations

The following symbols are used in this paper:
ARR = area replacement ratio;
BIS = Bureau of Indian Standards;
D = diameter of the column;
E = modulus of elasticity of soil;
EXP = experiment;
FE = finite element;
FEA = finite element analysis;
FEM = finite element method;
MCCF = multiple column composite foundation;
RD = relative density;
S = spacing between the sand compaction columns;
S/D = ratio between spacing to the diameter of columns;
SCC = sand compaction column;
SP = poorly graded sand;
SPT-N = standard penetration test N value;
U_X = displacement in x-direction;
U_Y = displacement in y-direction;
U_Z = displacement in z-direction;

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s/d = settlement of the footing / diameter of the footing;
r_e = relative element size factor;
R_{inter} = Interface friction factor between the plate and the sand;
γ = unit weight of sand;
φ = angle of internal friction;
ψ = dilatancy angle.

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Help rendered by the Head of the Department, Ocean Engineering at the Indian Institute of Technology Madras, Chennai with using PLAXIS 3D software is deeply acknowledged.

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