

Development of Design Charts for Sand Compaction Pile Method of Improvement for Loose to Medium Dense Sands



N. Aarathi and G. R. Dodagoudar

Abstract The improvement of soft clay deposits using stone columns is a well-established ground improvement technique in the western world. This technique has been well documented and has proper design codes for precise execution in the field. The sand compaction pile (SCP) method is a contemporary technique for stone columns and has limited literature related to the strength characteristics of the loose to medium dense sand deposits treated with SCP. The available studies on the SCPs installed in cohesionless deposits focused on the improvement by indirectly assessing the SPT-N values pre- and post-installation of the SCPs. The widespread implementation of the SCP technique in recent years has increased the need for a more direct evaluation of the improvement. Earlier studies in this regard have revealed that the available design solutions are based on the type of installation equipment, their working efficiency, and accumulated field data. However, it is found that there are no generic design codes for the direct estimation of the ultimate bearing capacity of the SCP improved cohesionless deposits. To meet the design requirement for the SCP treated ground, a series of experimental and numerical investigations are performed in the present study to arrive at a direct framework in the form of design charts based on the pressure-settlement response of the treated ground. The developed design charts give the ultimate bearing capacity (UBC) of the treated sand deposit for the known initial relative density (RD) of the deposit, spacing and diameter of the SCPs, size of the footing, and for the specified target unit weight required for the intended application. It is concluded that the design charts will be of preliminary use to the design engineers to directly evaluate the UBC of the SCP improved loose to medium dense cohesionless deposits as part of the SCP method of ground improvement. It is expected to have more field-scale experiments and in-depth analysis before implementing these charts for actual field execution.

Keywords Sand compaction pile method · Design chart · Ultimate bearing capacity · Bearing capacity factor · Single column · Multiple columns

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Notation

ARR	Area replacement ratio
D	Diameter of the SCPs
EXP	Experiment
FEA	Finite Element Analysis
ICCF	Individual Column Composite Foundation
MCCF	Multiple Column Composite Foundation
S	Spacing between the SCPs
SCP	Sand Compaction Pile
UBC	Ultimate Bearing Capacity
d	Width/diameter of the foundation
γ	Insitu density of the soil-pre and post improvement
ϕ	Internal angle of friction of the pile material

1 Introduction

The stone column technique of ground improvement is a versatile method often adopted in the Western Hemisphere of the globe to attend issues related to geotechnical engineering. The inclusion of these granular columns not only improves the engineering properties of the composite ground but also accelerates the drainage to achieve the maximum settlement before the construction of the superstructure. One of the main reasons for the widespread implementation of the method is the availability of design methodologies (both empirical and non-empirical with simpler assumptions). These design procedures majorly include the framework in the form of charts, where one can find the unknown value (e.g., ultimate bearing capacity (UBC), stiffness improvement factor, β), with a few known factors (e.g., spacing and diameter of the columns, area replacement ratio adopted, internal friction angle of the columns, etc.). Promising notable design theories that are still used are proposed by Greenwood (1970), Hughes and Withers (1974), Hughes et al. (1975), and Balaam et al. (1977). Design methodology proposed by Priebe (1995) is still regarded as the most employed method to construct stone columns. Thus, it can be stated that design frameworks are abundant for adopting the stone column technique which resulted in its massive deployment worldwide.

Sand compaction piles (SCPs) are usually constructed by driving a casing pipe closed at the bottom with a special shoe through a loose to firm sand or a very soft to firm silt or clay stratum using a vibrator/ hammer located at the top of the casing. After driving, the casing pipe is filled with sand or a mixture of sand and aggregates in stages. The native sand is then densified by repeatedly raising and lowering the vibrating pipe as it is withdrawn from the ground. At this juncture, it can be clearly evident that these sorts of comprehensive design theories are found to be hardly any when the technique of sand compaction piles is taken into account

and this forms the need for the present study. Upon reviewing the published data available on the sand compaction pile method, few studies limited to (D'Appolonia 1953; Webb and Hall 1969; Brown 1977) stated design methodologies in the form of charts. However, in these studies, the RD achieved was related to the dimensionless influence coefficients which were obtained by the extent of improvement achieved by the different types of vibroflot machines used for the installation of the SCPs. The major factor considered was the radial zone of improvement measured from the center of the SCP for a particular type of vibroflot machine employed in the construction, i.e., the design charts are specific to a particular type of vibroflot machine used. The Japanese geotechnical society (1998) has proposed a procedure using a pre-selected diameter of the SCP and target standard penetration test value (SPT-N) to design the SCP technique for a particular site. Kitazume (2005) has proposed a few design charts based on the accumulated field data obtained from the original SPT-N value of the native deposit and the target SPT-N value to be achieved for the site in order to design the improvement scheme using the SCPs.

The design charts proposed from the above past studies mentioned have considered the efficiency of vibroflot machines used for the construction of SCPs, and SPT-N from accumulated field data from sites. Thereby, these available charts do not apply to all field cases worldwide. Out of the few design frameworks available in the literature, as seen above, there are no proper solution methods available for the direct estimation of the ultimate bearing capacity (UBC) or axial capacity of the SCP improved sand deposits in the form of ready-to-use formulae and design charts. Moreover, a systematic framework involving the properties of the ground to be improved and the degree of improvement to be achieved, the size of the footing employed, and the characteristics of the SCPs to be installed are still lacking. Also, there are no existing generic design codes for sand compaction piles installed in sands unlike the other ground improvement techniques such as stone columns, dynamic compaction, etc. in India. Therefore it can be stated that even after a rough five-decade had passed since its invention, there is no commonly available design procedure available in the form of ready-to-use codes for computing SCP design techniques for a given site, unlike stone columns.

This forms the basis for the present study to develop the design charts using a few of the basic parameters of the sand deposit and SCPs for the direct estimation of the UBC of the SCP improved ground. The present attempt is an outcome of a detailed experimental (EXP) and finite element (FE) investigations conducted by Aarthi (2020). A series of plate load tests (using circular footing plate) were conducted (both in the laboratory (Fig. 1) and numerical simulation (Fig. 2)) on single SCP (Individual Column Composite Foundation—ICCF) and three SCP groups (Multiple Column Composite Foundation—MCCF) which include the compaction pile and their respective tributary areas too. The results obtained from the above tests are developed into a design framework from which one can directly estimate the ultimate bearing capacity of the SCP improved sandy deposits. The paper presents the results attained from the above tests in a nutshell in the form of design charts.

The input data needed to use these charts are the following: Initial relative density (RD) of the original ground to be treated, diameter (D) and spacing (S) of the SCP,

Fig. 1 Layout of SCP in test tank for experimental investigation in the laboratory (for 2D spacing)

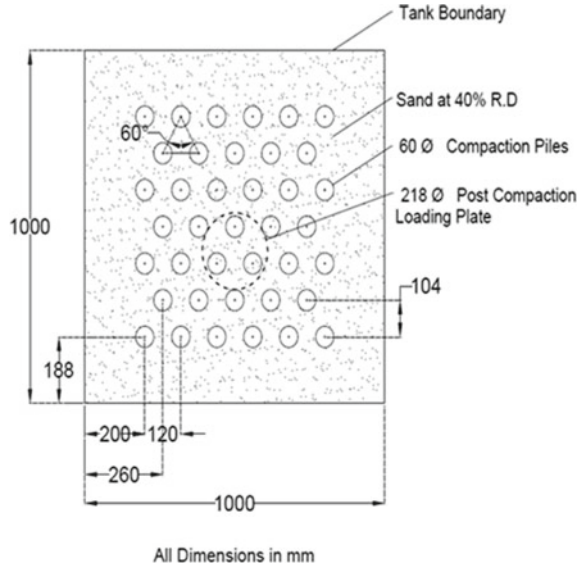
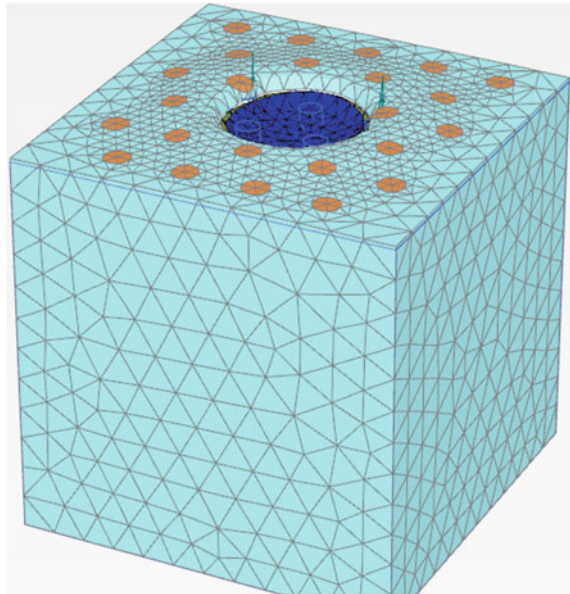


Fig. 2 View of the numerical model for lab-scale dimension showing failure after load application



target bulk unit weight of the sand deposit (γ) which is used for the assessment of the improvement, and diameter of the foundation (d). The output of the design chart is the UBC of the SCP improved sand deposit. The enhanced UBC of the SCP improved ground can be evaluated well in advance before the execution of the SCP treatment using the developed design charts. The design charts are developed for the

equilateral triangular pattern of the SCPs installed in loose to medium dense sand deposits with fines content around 5%.

2 Factors Affecting the Design of SCP Treatment

The design of ground improvement using the SCP technique involves consideration of many factors that commonly affect the performance of the sand compaction piles for the proposed site. The factors are as follows:

- Insitu density of the soil—pre and post improvement (γ),
- Type of installation of the SCPs,
- Spacing between the SCPs (S),
- Diameter of the SCPs (D),
- Number of SCPs under loading (Single [ICCF] or Multiple [MCCF]),
- Type of installation pattern (Triangular or square or rectangular),
- Depth of improvement needed (L),
- Backfill material (pile material),
- Internal angle of friction of the pile material (ϕ),
- The withdrawal technique of the installation mechanism,
- Width/diameter (d) of the foundation,
- Area replacement ratio (ARR), and
- Vertical load intensity.

3 Design Charts for Axial Capacity of MCCF: Experimental Results

An extensive experimental study is carried out by Aarathi et al. (2019) to investigate the pressure-settlement response of the sand compaction pile improved cohesionless deposits. The results obtained from the above study are considered along with a comprehensive finite element (FE) studies performed by Aarathi (2020) using PLAXIS 3D, to aid in the development of design charts in the present paper. A humble beginning has been made to propose the design charts based on the extensive results of laboratory experiments and FE simulations performed on the single SCP (Individual Column Composite Foundation—ICCF) and SCP group (Multiple Column Composite Foundation—MCCF). Out of the many design charts developed the present section deals with the design chart developed using laboratory experiments presented in Aarathi et al. (2019). The following factors are considered to develop the design chart for the MCCF:

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

Table 1 Range of parameters employed in laboratory investigation

Parameter	Range
Initial relative density (RD) (%)	30, 40, 50, 60
Length of SCP (L)	500 mm (Leaving more than 4.5D below the bottom of the tank to avoid boundary effects)
Diameter of SCP (D)	600 mm
Spacing/Diameter (S/D) ratio	1.5, 2, 2.5, 3, 3.5
Size of the plate (d)	164, 218, 273, 328, and 382 mm For MCCF, from 1.5 to 3.5D spacing between the SCPs

The following two dimensionless numbers are related to each other in the design chart:

1. S/D ratio \Rightarrow Spacing of the SCP (m)/Diameter of the SCP (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).

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 design chart 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. Table 1 as presented below indicates the range of parameters that has been employed for the experimental investigation.

The design charts are developed for the equilateral triangular pattern of the sand compaction piles installed in loose to medium dense sand deposits with minimal fines content. The design chart as shown in Fig. 3 is established for the SCPs installed in sandbed by employing drop hammer method of installation and hence can be applied to similar executions. Owing to the economic viability of lab-scale experimentation, the drop hammer method of installation was chosen to drive the SCPs in the study. In the laboratory, the SCPs were installed by driving the casing in line with the desired pile configuration using a guiding rod and hammer. A hammer weight of 10 N was made to slide over a guide rod to drive the casing. The casing was driven with its bottom closed to prevent the entry of sand and the sand is fed through the casing to install the SCPs. Upon reaching the required depth, the hammer was removed and the calculated weight of sand was poured into the casing with the SCP occupying the inner diameter of the casing.

The installed SCP has to have the RD in the range of 70–75% for the effective utilization of the chart. The unit weight of the sandbed after improvement for the lab-scale experiment is obtained by back-calculating the relative density values by noting the penetration value using a self-weight penetrometer fabricated exclusively for facilitating the study. For field applications, the target relative density (RD) or the unit weight (γ) has to be fixed a priori before the execution of the SCP improvement technique. The RD or the unit weight of the unimproved ground can be ascertained by conducting the SPT, CPT, and geophysical tests also.

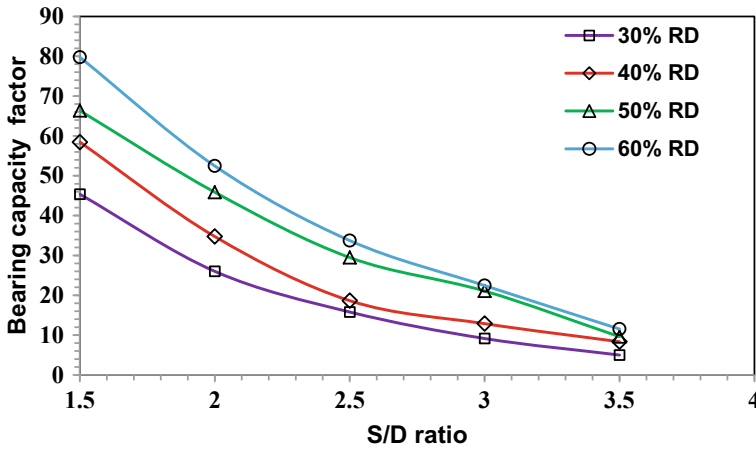


Fig. 3 Design chart for estimating the axial capacity of MCCF: Experimental results

4 Design Charts for Axial Capacity of MCCF: FE Results of Lab-Scale Model

Likewise in the previous section, a design chart is developed from the results of the FE simulation of the lab-scale SCP model. The FE results obtained from the preliminary sensitivity analyses are made use of in the development of the chart. In the parametric analyses, the initial RD of the sandbed is varied from 30 to 60% and the spacing between the SCPs is varied from 1.5 to 3.5D. The footing was supported by the three SCP groups (i.e., MCCF). The design chart will give a complete picture of the UBC or axial capacity attained from the FE results of the lab-scale SCP model as shown in Fig. 4. For the pre-selected S/D ratio of the SCP technique, size of the footing, and the required target unit weight to be achieved for the deposit, the design chart 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 w. r. t. the range of the initial RD (30 to 60%) of the sand deposits. The UBC values estimated from Fig. 4 are on average 12% less compared to those estimated from Fig. 3. Further refinements are needed in the finite element simulation studies related to the modeling of lab-scale SCP problem.

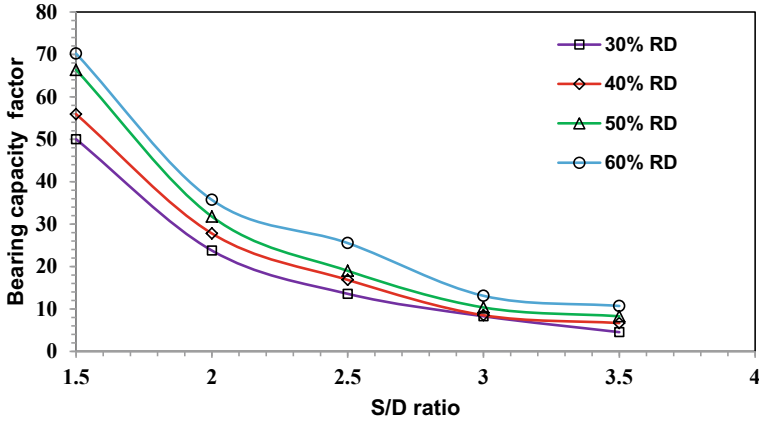


Fig. 4 Design chart for estimating the axial capacity of MCCF from FE results of the lab-scale model

5 Design Chart for Axial Capacity of ICCF: Experimental and FE Results

The FE simulation of the individual column composite foundation (ICCF) is also performed for the lab-scale model of the footing supported on a single SCP and its tributary area. The size of the footing is equal to effective diameter (d_e) = 1.05S, where S is the spacing between the SCPs. The experimental results were obtained for the ICCF installed in a sandbed with an initial RD of 40% where the spacing is varied from 2 to 3D. The experimental results are compared with the FE results and are used to develop the design chart as shown in Fig. 5.

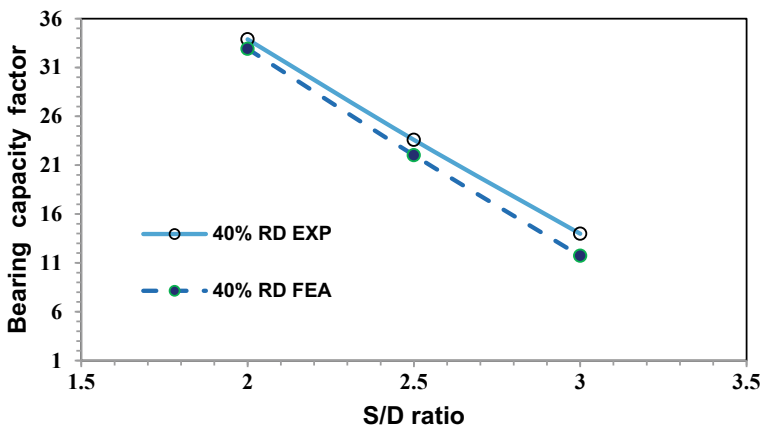


Fig. 5 Design chart for estimating the axial capacity of ICCF from experimental and FE results

As in the previous section, Fig. 5 also underestimates the axial capacity in the FE results, for the SCP treated ground for a given site condition in comparison to the experimental results. With the help of the design chart (Fig. 5), one can estimate the ultimate bearing capacity of the single SCP along with its tributary area loaded in the field, for the target unit weight of the deposit for which the improvement is proposed to be undertaken.

6 Design Chart for MCCF: Experimental and Field-Scale FE Results

In this section, an effort is made to combine the lab-scale experimental results and those obtained by the FE simulation of the field-scale SCP treated sand deposits to develop the design chart. Figure 6 gives the design chart for MCCF constructed in the sand deposit making use of the experimental and field-scale FE results. The SCPs are supposed to have a relative density in the range of 70–75% for effective utilization of the chart. The scale effect is evident as seen from the figure. A larger size laboratory experimental setup and rigorous field-scale experimentation are necessary to reduce the scale effects. Centrifuge experiments can also be performed to reduce the scale effects. However, in the present attempt, the results of scale-down laboratory experiments are used in the development of the design chart. The FE results obtained for the field-scale SCP problem need to be validated either using prototype or centrifuge results. Nevertheless, the design chart developed using the field-scale FE results can be used to make the preliminary designs for the SCP technique. In the FE simulation, the loaded footing comprises the three SCPs along with its tributary area, installed in the sand deposit with a layer of SCPs surrounding the footing as recommended by Han (2015).

Figure 6 also shows the regression equations developed using the experimental and FE results. The independent variable x in the equation designates the S/D ratio and y the *Bearing Capacity Factor*. These equations are applicable for the medium dense sand deposits. It can be stated that the regression equation developed for the estimation of the ultimate capacity of the MCCF using the FE results of the field-scale SCP problem is reliable. Similarly, a few more design charts can be developed by considering the different initial RDs for the field-scale problem of the SCP improved sand deposits. It is also evident from Fig. 6 that, the developed design framework, accommodates the results of both lab-scale experiments and field-scale experimental results obtained by finite element analyses.

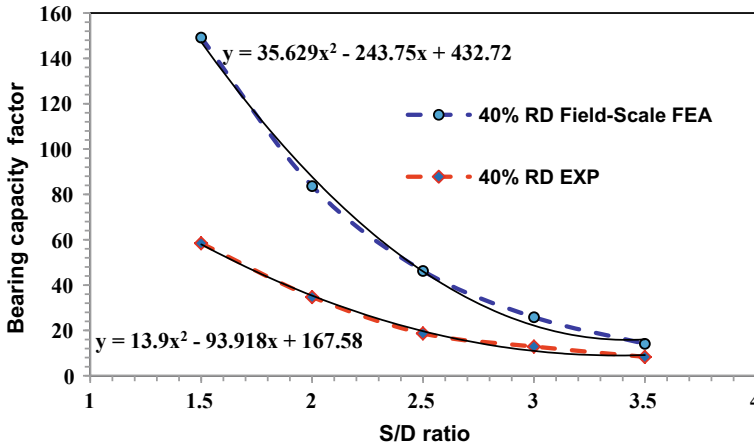


Fig. 6 Design chart for estimating the axial capacity of MCCF from lab-scale experimental results and FE results of the field-scale model

7 Conclusions

The paper presents a chart-based design framework based on lab-scale experimental work and FEA that needs to be validated and modified based on field-scale testing on cohesionless deposits improved by sand compaction piles. The design charts developed using laboratory experiments are found to have scale effects. Only a few basic parameters are needed to use the design charts to obtain the ultimate bearing capacity of the footing resting on a single sand compaction pile (SCP) and SCP group. These charts can be used to estimate the ultimate bearing capacity of the SCP treated sand deposit with pre-selected target unit weight of the treated deposit, diameter, and spacing of the SCPs to design the ground improvement scheme for the SCP method. The design chart developed using the results of finite element analysis of the field-scale SCP problem can be used to estimate the ultimate bearing capacity and accordingly the SCP technique be used to treat the cohesionless deposits in the field. More finite element analyses of the field-scale problem are further needed along with their validation for field-scale projects to develop more robust design charts that will be applicable to all conditions of the cohesionless deposits.

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