Three-dimensional numerical modeling of sand compaction piles in soft clay deposit

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ABSTRACT
Sand compaction piles (SCP) are considered as one of the potential methods for improving ground stability. In the SCP method, compacted sand piles, either in a square or equilateral triangular pattern, are installed into the soft ground at a desired depth to form a composite foundation bed that acts as a stiffer material to support the super-structural loads. Previous studies on the SCP for estimating the bearing capacity of SCP reinforced soils are primarily based on analytical approaches. However, most of these analytical methods are based on simplified theoretical assumptions that might not represent the actual ground condition. This study focused on the development of a three-dimensional finite element (FE) model to simulate the composite ground condition with SCPs installed in a soft clay deposit. A 2 m x 2 m square footing was placed on the SCP reinforced ground to evaluate the bearing capacity of the soil. The FE results showed that the ultimate bearing capacity of the square footing is 21% higher than the analytical solution. Furthermore, the parametric study showed that a triangular arrangement of the SCPs provides 25% higher bearing capacity than the square pattern. Finally, a design flow-chart was formulated to calculate the composite ground parameters for SCPs and the surrounding soil considering the effect of compaction and resulting disturbance in the surrounding soils during the SCP installation.

RÉSUMÉ
Les pieux de compactage du sable (SCP) sont considérés comme l'une des méthodes potentielles pour améliorer la stabilité du sol. Dans la méthode SCP, des tas de sable compactés, soit dans un motif triangulaire carré ou équilatéral, sont installés dans le sol meuble à la profondeur souhaitée pour former un lit de fondation composite qui agit comme un matériau plus rigide pour supporter les charges super-structurelles. Les études antérieures sur le SCP pour estimer la capacité portante des sols renforcés SCP sont principalement basées sur des approches analytiques. Cependant, la plupart de ces méthodes analytiques sont basées sur des hypothèses théoriques simplifiées qui pourraient ne pas représenter l'état réel du sol. Cependant, la plupart de ces méthodes analytiques sont basées sur des hypothèses théoriques simplifiées qui pourraient ne pas représenter l'état réel du sol. Cette étude s'est concentrée sur le développement d'un modèle tridimensionnel d'éléments finis (FE) pour simuler l'état du sol composite avec des SCP installés dans un dépôt d'argile molle. Une superficie de 2 m x 2 m carrés a été placée sur le sol renforcé SCP pour évaluer la capacité portante du sol. Les résultats de l'EF ont montré que la capacité portante ultime de la pied carré est supérieure de 21 % à celle de la solution analytique. En outre, l'étude paramétrique a montré qu'une disposition triangulaire des SCP offre une capacité portante 25% plus élevée que le motif carré. Enfin, un organigramme de conception a été formulé pour calculer les paramètres composites du sol pour les SCP et le sol environnant en tenant compte de l'effet du compactage et de la perturbation qui en résulte dans les sols environnants lors de l'installation du SCP.

1 INTRODUCTION

Soft soils are widely found in various parts of Canada resulting in large settlements and other ground instability issues (Gnanendran et al., 2015). There are various ground improvement methods available such as densification by compaction, replacement of the soft layers, chemical stabilization by grouting and mixing, geosynthetic reinforcement, thermal and biological treatments, sand compaction piles, etc. Sand compaction piles (SCPs) are widely known as a column-based ground improvement technique, especially for challenging ground condition due to soft soil deposits. This method involves driving a hollow steel pipe into the ground where the bottom is closed with a collapsible plate down to the required depth. The pipe is then filled with sand and later withdrawn while the air pressure is directed against the sand inside the pipe (Aboshi et al., 1979). The various uses of the SCPs include the increase of bearing capacity, liquefaction mitigation, and speeding up the consolidation time (Feng et al., 2020). Based on the casing driving and method of sand injection it can be of vibratory, non-vibratory and sand injection type SCP (Harada and Ohbyashi, 2017). In clayey soils, SCP serves primarily as a ground reinforcement and improves bearing capacity, and reduces settlement (Hossain et al., 2020). This method is also claimed as a leading countermeasure against soil liquefaction as it combines densification and drainage for ground improvement (Harada and Ohbyashi, 2017). Research has shown that the sand compaction pile can be a cost-effective and adaptive option compared to preloading, dynamic compaction, deep replacement, etc. (Hoque and Alamgir, 2014).

The efficiency of the SCP technique depends on several factors, e.g., size of the piles, spacing of the piles, type of granular material, and arrangement of the piles at the site. The modeling of a SCP reinforced soil is usually complex in nature due to the installation effect to the surrounding soft soils. Previous studies on both analytical and numerical simulations are available in the literature. The analytical solutions are limited by the number of assumptions to simplify the calculations (Han 2015). As a result, these analytical solutions often suffer from predicting the realistic bearing capacity of the SCP reinforced soil i.e., they end up with either overestimating or underestimating the capacity due to the lack of a real ground scenario. Therefore, numerical solutions are often considered as an improved method for predicting the bearing capacity of the SCP reinforced soil. Previous researchers considered various complex ground conditions, e.g., effect of driving force, disturbance of surrounding soils due to the expansion of cylindrical cavities, effect of elasto-viscoplasticity, increase in lateral earth pressure, etc. in their numerical models (Zhang et al., 2021, Saxton and McCabe 2015, Collins 1996, Vesic 1972). However, these numerical models are complex in nature, and therefore, a simple yet realistic approach to estimate the bearing capacity of the composite ground is required for the increased demand of the use of SCPs for ground improvement.

In this study, a three-dimensional finite element (FE) model was developed to estimate the bearing capacity of a square footing placed on a SCP composite soil. A design chart was formulated to calculate the composite ground parameters for implementing in numerical models. Finally, a parametric study was conducted by varying the depth of improvements as well as the arrangement of compaction piles.

2 PROBLEM DEFINITION

Figure 1 illustrates the model geometry used in this study. Two model geometries were considered one with a natural ground (Fig. 1a) and one with composite ground with SCPs (Fig. 1b). To validate the numerical model, analyses were first conducted considering a square footing (2 m × 2 m) placed on the ground surface of the soft clay (Fig. 1a). The footing was considered at the surface of the ground for the simplicity of numerical modeling. A vertical concentric displacement was applied on the footing until it reached its failure load. Following the validation of the FE model, SCPs were installed in the ground to the full depth of the soil block (Fig. 1b). The problem was then re-analyzed to determine the bearing capacity of the SCP reinforced ground. Additional depth of soft soil was considered under the SCPs in the second model to avoid boundary effects on the SCPs.

For both models, H = 30 m, L = W = 9 m, and H_{scp} = 10 m were assumed as shown in Figure 1. The diameter and spacings of SCP are taken as 0.8 m and 1.5 m, respectively. Equilateral triangular pattern was chosen for the base case SCP model. The depth of the water table was considered 1 m below the ground level. To take advantage of the symmetry, only one-fourth of the model was considered in the numerical analyses. A sensitivity study on the FE model dimension confirmed that FE model dimensions as shown in Figure 1 are sufficient to avoid any boundary effects on the FE results.

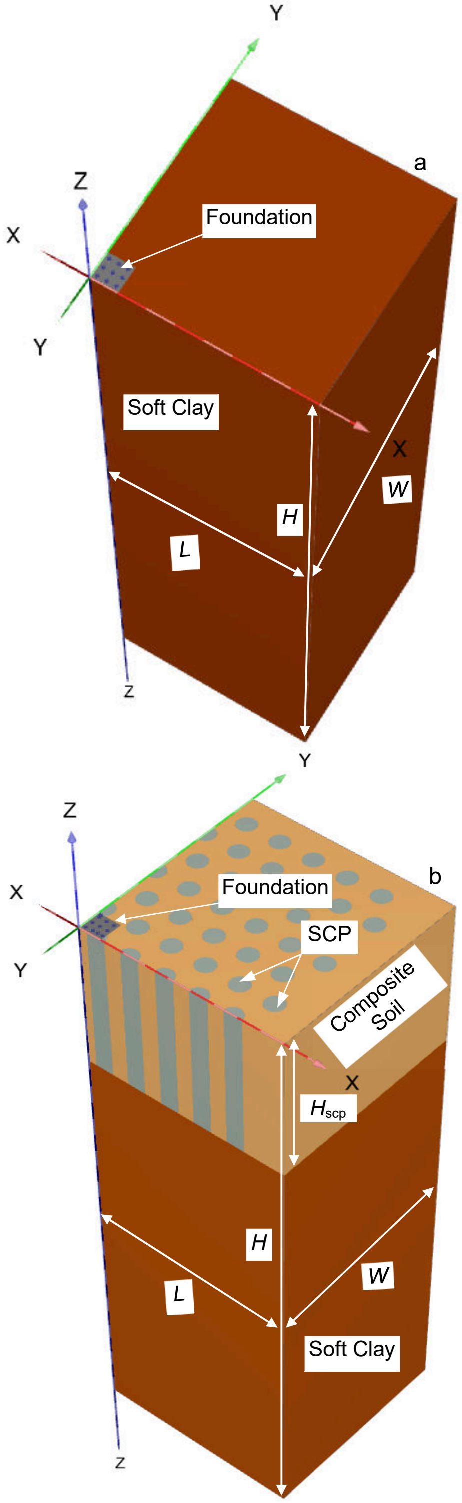


Figure 1. Details of FE model: a) natural ground, b) composite ground after SCP installation (not to scale)

3 NUMERICAL MODELING

A commercially available FE software package, PLAXIS 3D Advanced (version 21.00.00.223) was used for all the numerical analyses. 10-noded tetrahedral elements were used to discretize the domain. Global mesh generation along with enhanced mesh refinements techniques (to mesh the foundation) available in the PLAXIS software was adopted. A coarseness factor of 0.005 was used for meshing the foundation area whereas a coarseness factor of 0.5 was used for the rest of the domain.

Roller supports were assigned to all the vertical faces allowing the soil movement along the Z-axis only, while hinge supports were used at the bottom surface of the domain.

The loading on the foundation was simulated by applying a prescribed displacement of 1 m vertically downward along the negative Z-axis (u_z = -1.00 m). The load was applied in two steps. The initial step simulates the geostatic condition to generate in-situ stresses within the soil. Then the incurred displacements and small strains were set to zero prior to application of the prescribed displacement in the loading phase. Note that no suction effect was considered in this study.

3.1 Material Parameters

The soil was modelled as an elastic-perfectly plastic material using the classical Mohr-Coulomb soil constitutive material model. The stiffness of the soil and SCP were assumed to be constant throughout the depth. The geometry and material parameters for both soft clay and SCP are listed in Table 1.

Table 1. Material properties of soft clay

Parameter	Value
Undrained shear strength[1], s_u	20 kPa
Undrained Young's modulus[2], E_u	500 s_u
Drained Poisson's ratio in FE analysis, υ	0.3
Saturated unit weight of soil, γ_{sat}	19 kN/m^3
Unsaturated unit weight of soil, γ	18 kN/m^3

[1] natural ground before improvement
[2] derived from Saha et al., 2019

3.2 FE Model Validation

The FE model was first validated for the square footing (2 m × 2 m) placed on the ground surface of the soft clay without considering any SCP (Fig. 1a). Figure 2 shows the stress vs displacement plot obtained from this analysis. Figure 2 shows a reasonable agreement between the FE model (r_e = 0.5) and the analytical solution (CFEM 2006). Results from two other analytical solutions proposed by Terzaghi (1943) and Meyerhof (1963) are also plotted in Fig. 2.

To eliminate the effect of mesh size, a set of analyses were conducted for different relative element size factors r_e = 0.5-2.0. Figure 2 shows that as the mesh size decreases, the ultimate bearing capacity, q_{ult} (the maximum shear stress in soil) converges towards the analytical solutions. The greater the r_e value, the higher the offset from the analytical result. However, r_e = 0.5 (very fine mesh) resulted in the closest agreement with the analytical solutions. Therefore, this mesh size (r_e = 0.5) was adopted in rest of the study. Dey et al. (2019) also showed that for analysis of similar problems in PAXIS, r_e = 0.5 results in mesh convergence.

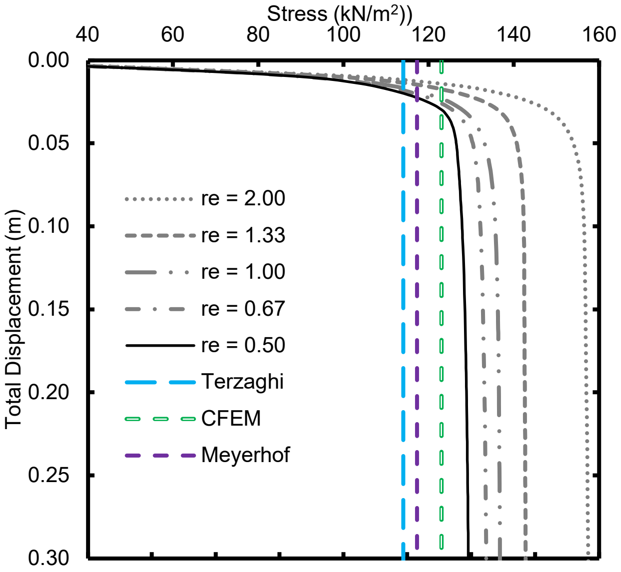


Figure 2. Mesh convergence analysis and model validation

3.3 Modeling of SCP

When SCPs are installed within a soft clay deposit, they act like deep replacement (Han 2015). The columns with the surrounding soil form a composite ground that offers higher bearing capacity, reduces settlement, increases shear strength, and decreases the chance of liquefaction. This causes an improvement in the SPT value of the soil both at the middle of the SCP columns and in the midway of the columns as shown in Fig. 3.

The improvement in SPT value due to installation of SCP depends on the area replacement ratio, a_s defined by Han 2015 as follows:

$$a_s = C\left(\frac{d_c}{s}\right)^2 \quad [1]$$

Here, C is the coefficient for arrangement pattern of SCPs, d_c is the diameter of the SCP, and s is the spacing between the sand columns.

The procedure of determining the improved SPT values and how those parameters were incorporated in the numerical model are shown in Fig. 4. The analytical ultimate bearing capacity of the composite ground has been computed using the equivalent SPT value of the composite ground, N_{eq} defined by Han (2015) as follows:

$$N_{eq} = a_s \times N_2 + (1 - a_s) \times N_1 \quad [2]$$

Improved undrained shear strength of the composite ground was then recalculated using the following correlation suggested by Terzaghi and Peck (1948 & 1967):

$$s_{u,i} = 6 \times N_{eq} \quad [3]$$

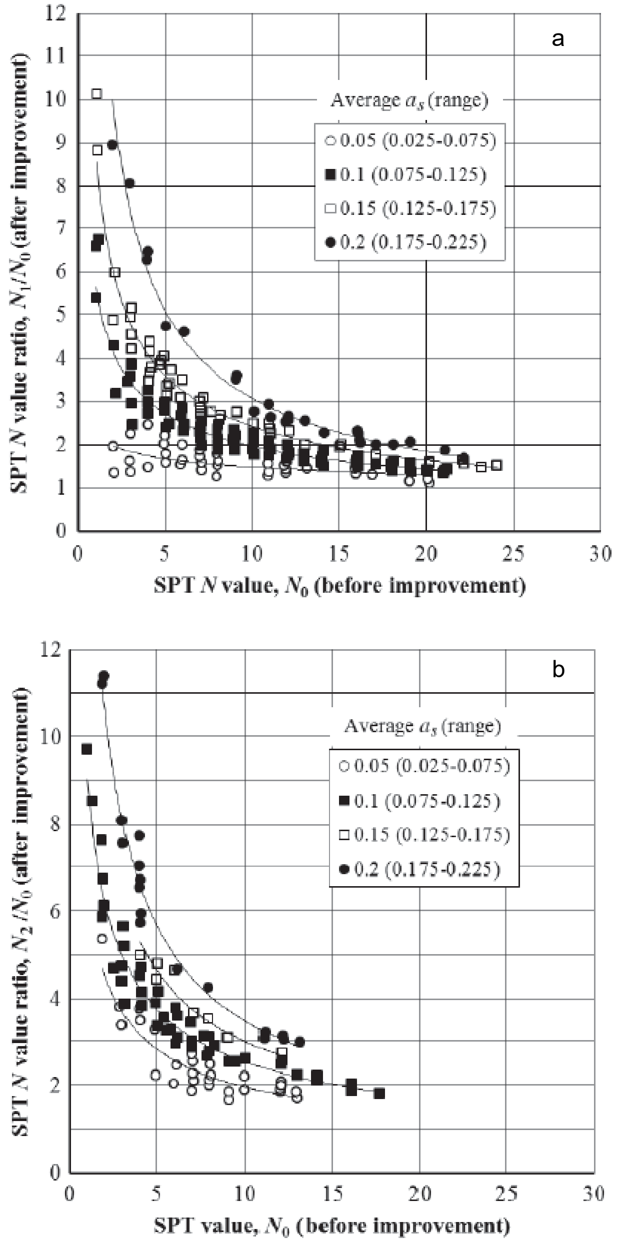
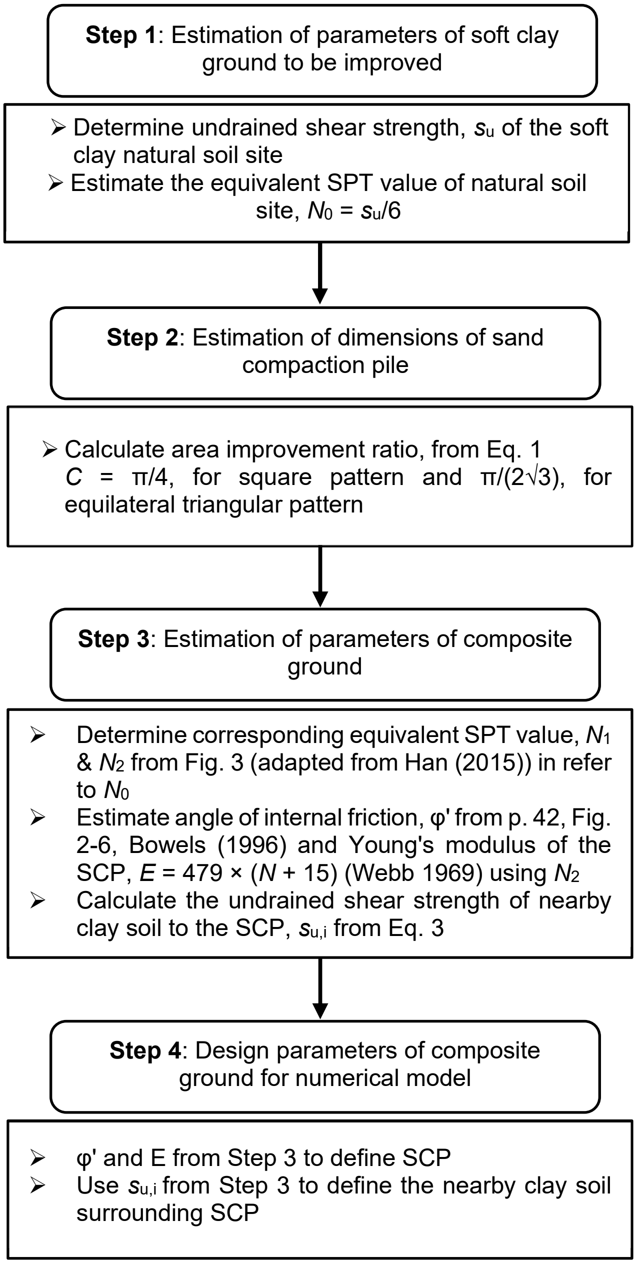


Figure 3. SPT value before and after SCP installation a) midway between the columns b) at the middle of sand columns (adapted from Han 2015)

Figure 5 illustrates the displacement vector plot for natural ground and composite ground. The failure pattern follows the conventional theoretical shear failure pattern of a footing foundation. The horizontal extent of the failure surface increases from 2.1 m (for natural ground) to 2.5 m (for composite ground with SCP).



Step 1: Estimation of parameters of soft clay ground to be improved

- Determine undrained shear strength, s_u of the soft clay natural soil site
- Estimate the equivalent SPT value of natural soil site, $N_0 = s_u/6$

Step 2: Estimation of dimensions of sand compaction pile

- Calculate area improvement ratio, from Eq. 1 C = π/4, for square pattern and π/(2√3), for equilateral triangular pattern

Step 3: Estimation of parameters of composite ground

- Determine corresponding equivalent SPT value, N_1 & N_2 from Fig. 3 (adapted from Han (2015)) in refer to N_0
- Estimate angle of internal friction, φ' from p. 42, Fig. 2-6, Bowels (1996) and Young's modulus of the SCP, $E = 479 \times (N + 15)$ (Webb 1969) using N_2
- Calculate the undrained shear strength of nearby clay soil to the SCP, $s_{u,i}$ from Eq. 3

Step 4: Design parameters of composite ground for numerical model

- φ' and E from Step 3 to define SCP
- Use $s_{u,i}$ from Step 3 to define the nearby clay soil surrounding SCP

Figure 4. Design chart for composite ground parameters.

SCPs also cause the vertical failure surface to extend deeper from 0.75 m to 1.1 m. Thus, SCP installation offers a higher bearing capacity of the ground by widening and deepening the failure surface.

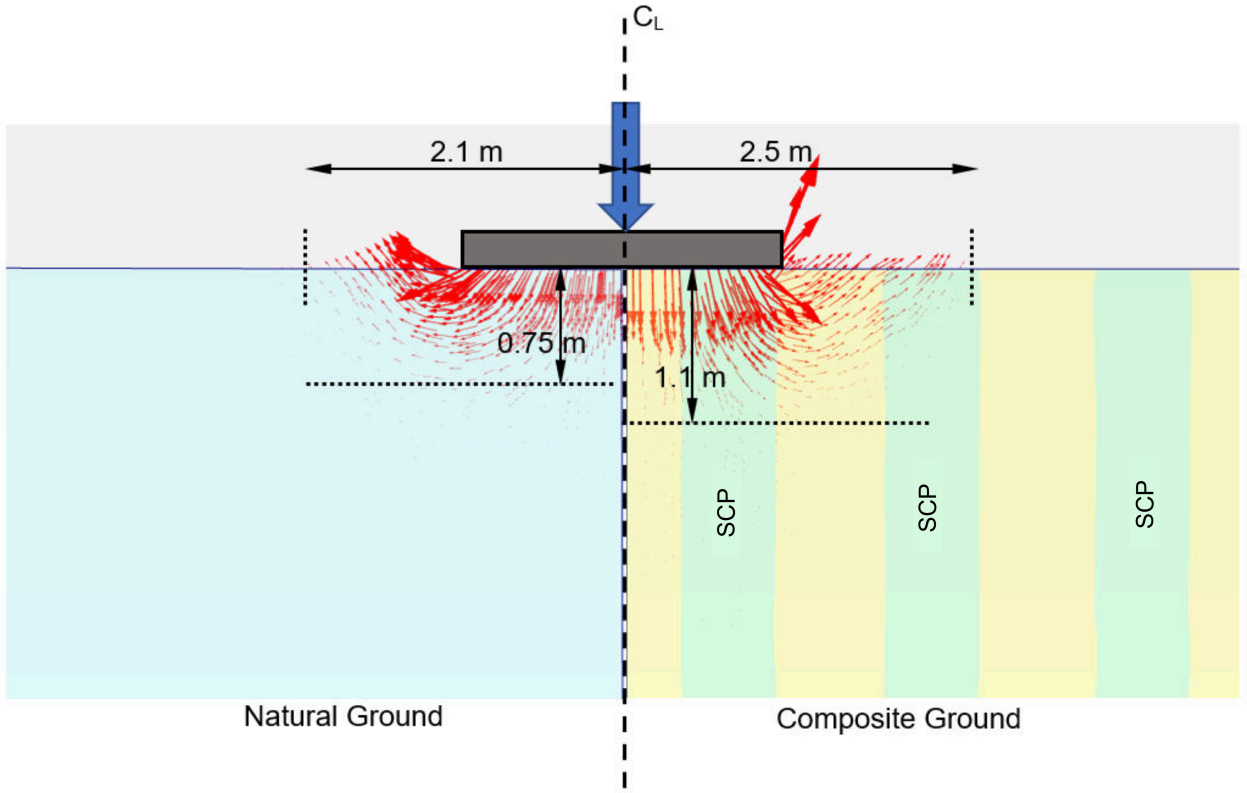


Figure 5. Displacement contour plot (a) Natural Ground (b) Composite Ground

Figure 6 shows a comparison of the bearing capacity of soil with and without SCPs. The bearing capacity of the SCP reinforced soil is found as 970 kN/m^2 which is 7.4 times higher than the bearing capacity of the soft soil without SCP (130 kN/m^2).

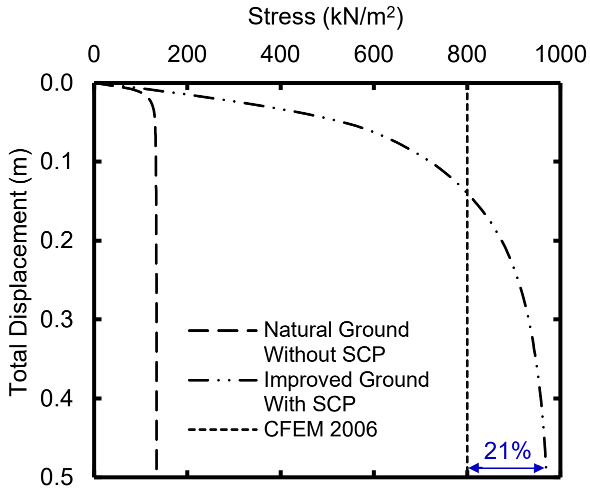


Figure 6. Bearing capacity improvement due to SCP installation

The analytical ultimate bearing capacity (CFEM 2006) calculated from improved equivalent SPT value of the composite ground is found as 800 kN/m^2 which is ~21% less than that obtained from numerical analysis (Fig. 6). In other words, the analytical approaches provide more conservative solutions for the ultimate bearing capacity of a composite ground. However, the analytical solutions can significantly underestimate the actual improved bearing capacity of the SCP reinforced soil.

4 PARAMETRIC STUDY

The factors affecting the performance of SCP are diameter and spacing of the sand columns, depth of SCP and the pattern in which SCPs are installed. Since changing the diameter or spacing of SCP will cause a change in the area replacement ratio, a_s the parametric study was conducted keeping the d_c/s ratio unchanged i.e., only one parameter was changed at a time.

4.1 Effect of depth of SCP

The depth of SCP is dictated by the soil properties, site condition, and performance requirements (design bearing capacity). In this study, the SCP depth was varied from 0.08 H to 0.50 H (2.5 m to 15 m). Figure 7 represents ultimate bearing capacity of the composite ground for different SCP depths.

The ultimate bearing capacity, q_{ult} of the composite ground increases linearly with the depth of SCP up to a certain depth (0.33 H in this case). Beyond that depth, the ultimate bearing capacity does not increase with increase in depth of SCP. Therefore, the numerical approach provides a convenient solution to determine the optimum depth of SCP to be installed in the field based on site conditions and performance requirement level.

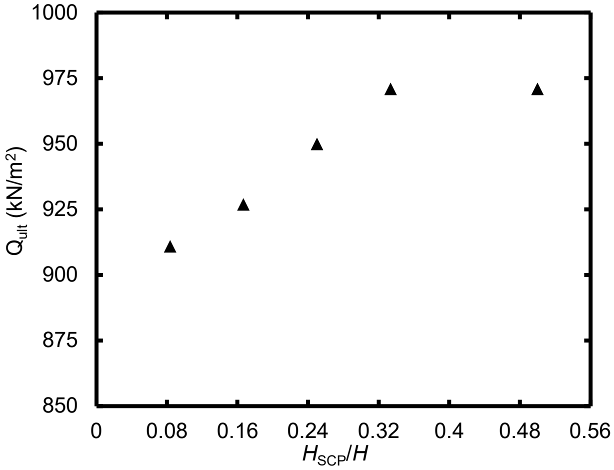


Figure 7. Variation of ultimate bearing capacity with depth of SCP

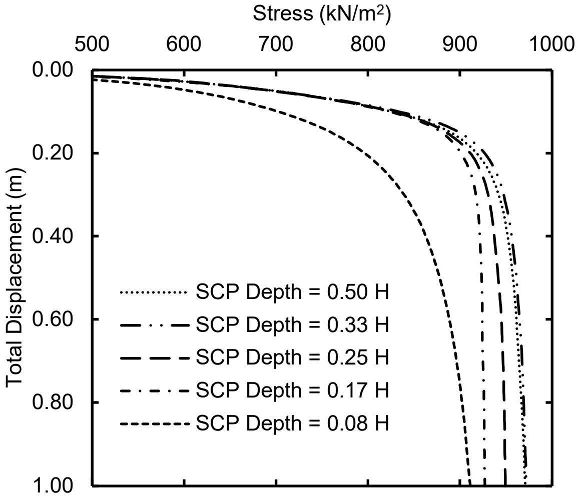


Figure 8. Stress-Deformation behaviors with depth of improvement

However, the correlation between the depth of SCP and the ultimate bearing capacity of the composite ground needs to be investigated further and is left for future study. Figure 8 represents the stress-displacement behavior of the composite ground with varying SCP depths.

4.2 Effect of arrangement of SCP

Figure 9 represents two types of patterns for arrangement of SCPs: (a) Equilateral triangular pattern and (b) Square pattern. The diameter of the SCPs, d_c in both cases is kept the same. However, the spacing was calculated as 1.4 m for square pattern to keep the area improvement ratio, a_s same for both patterns.

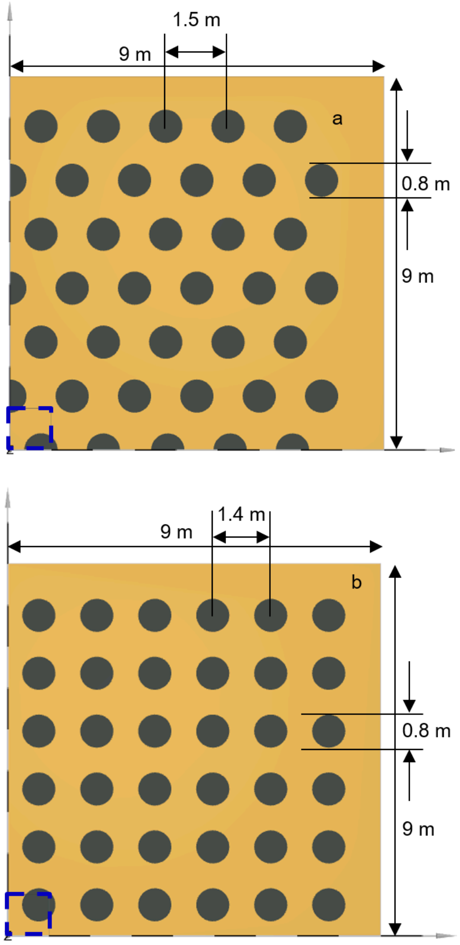


Figure 9. SCP arrangement pattern in plan view: a) Equilateral triangular pattern, b) Square pattern

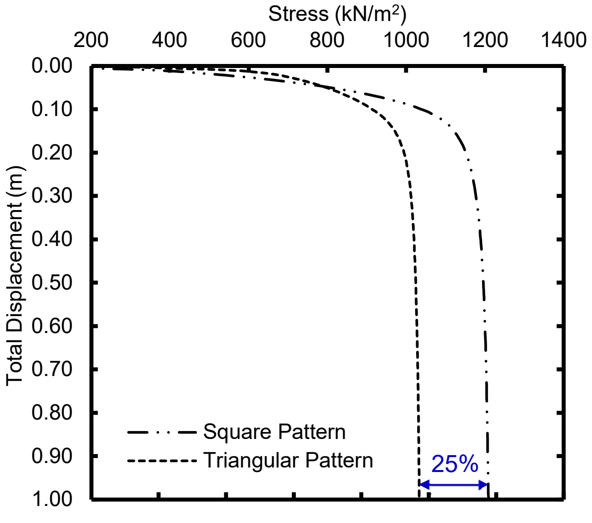


Figure 10. SCP Pattern effect on ultimate bearing capacity

The variation of ultimate bearing capacity of a composite ground for two different arrangement patterns of SCPs is illustrated in Figure 10. The stress-displacement curves show that the square pattern results in 25% more ultimate bearing capacity than equilateral triangular pattern.

5 CONCLUSIONS

Sand compaction piles (SCP) are a possible solution for improving the bearing capacity of soft ground. Although analytical solutions are available in the literature to design the SCPs, they can significantly underestimate the actual bearing capacity of the soil primarily due to the underlying assumptions. This paper aimed to develop a three-dimensional finite element (FE) model in PLAXIS 3D to better predict the bearing capacity of the SCP reinforced soil and understand the underlying mechanics. The FE model was first validated for a shallow footing resting on a soft clay soil. Based on the validated FE model, the analysis was then extended to calculate the bearing capacity of the SCP reinforced soil.

FE results show that the bearing capacity of the SCP reinforced soil can be 7.4 times higher than the bearing capacity of the soft soil without SCP. Besides, the analytical model significantly underpredicts the bearing capacity of the SCP reinforced soil. For example, the analytical ultimate bearing capacity calculated from improved equivalent SPT value of the composite ground using CFEM (2006) was found to be 21% lower than that obtained from the numerical analysis. A design chart was formulated to determine the composite ground parameters for numerical analysis. A parametric study on the effect of SCP depth and arrangement was also conducted. The results show that for same area improvement ratio, square arrangement of SCPs is more efficient than equilateral triangular pattern.

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