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The Settlement Evaluation of Improved Soft Clay Using Sand Columns and Partial Replacement Technique

Basim Jabbar Abbas
Civil Engineering
College of Engineering, Al-Muthanna University
AL-Muthanna, Iraq

***Abstract- Both* soil replacement and sand piles are generally used to improve the soft soils underneath the shallow foundations by reducing the settlement because of loads. The present search show studying improvement of the soft clay layer underlain a shallow foundation. The first improvement is by partially replaced sand in different depth, and the second is using sand columns. Analyses using finite elements methods (PLAXIS 3D program) were done to assess the settlement of soft clay which improved by compacted sand layers and floating sand piles. A spread footing under vertical load over improved clay was considered as a three-dimensional issue. For simulation by finite element models, the used materials of the soil were simulated by the standards of linear elastic-perfectly plastic Mohr-Coulomb theory. For the situation of soil replacement, settlement values from the software were compared to Janbu equations for evaluating the average settlement of flexible foundations on saturated clay soils. The results of sand columns which obtained from the Plaxis software were compared with results of Brom's analytical techniques. The obtained results demonstrated that the stress-settlement behaviour increases with increasing the thickness of sand layer. Using the sand columns technique reduces the settlement in different proportion depending on the number of sand columns and the value of applied pressure.**

Keywords — *soil improvement, soil replacement, Sand columns, settlement improvement factor, Janbu equations, Brom's analytical methods.*

1. INTRODUCTION.

Soft clay soils are broadly situated in numerous costal and surely known as the high compressibility and weak shear strength parameters. Development of any structures above the soft soils needs the some thinking about stabilities and settlements of the foundations for these structures which causes significant damages.

Use the reinforcement in site is performed by compacted sand, cement, or lime columns. This treatment leads to what is sometimes known as composite ground. Strength enhancement in sometimes are by small amounts of short lengths of plastic fibers or fiberglass which can be mixed with the soil for improvement soil strength. The major precaution is to use a fiber material that has an adequate durability in the hostile soil environment [1].

Using of different improvement techniques for weak soil especially soft clay is considered in a wide scope. The Geotechnical engineers have built up a few substitutes to take care of these issues, including utilization of vertical drain, Preoading method, geotextile technique, concrete piles, sand piles and columns of deep mixing [2]. Many methods to improve the soft clay were established by pervious researchers as [2], [3], [4], [5], [6], and [7] …..etc.

The bearing capacity of footings on soft clay can be additionally enhanced significantly by laying a layer of compacted granular fill in restricted thickness without/with geotextile or geogrid fortification at sand clay interface [8].

Black et al (2007) [9] studied experimentally the behaviour of soft kaolin clay samples (100 mm in diameter and 200 mm in height) were reinforced with vertical sand columns. They discovered that in the fully drained tests, the sample installed with a single column of 32 mm diameter exhibited better performance than the sample with three columns of 20 mm diameter, although the area replacement ratio in the case of the three 20 mm diameter columns was higher than that of the single 32 mm diameter column.

Abdel Salam (2007) [10] "investigated the effect of using different types and thickness of replacement layer on increasing bearing capacity and reducing consolidation settlement of soft clayey soil experimentally and concluded that, with increasing replacement layer thickness the vertical settlement decreased".

Zahmatkesh and Choobbasti (2010) [11] investigated the behaviour of soft clay improved by sand columns using 15-noded triangular finite element models (Plaxis software) for estimation the settlement in soft clay reinforced by sand columns. They concluded that the floating sand columns in high area replacement significantly reduced the settlement because of used frictional material.

So, the mechanism of bearing capacity failure for footing rested on soft clay can be improved from selective settlement to general bearing capacity failure at the end point of limited replaced sand column [3]

In this paper, a combination the low cost workable ground modified technique by situation replacement of soft soil and a high cost improvement technique using sand columns is presented. The first improvement technique is conducted by partial replacement of weak soil by compacted sand; this replacement method is only done beneath the footing area without the need to whole site replacement. The second improvement technique is done by injecting number of circular tube filled with compacted sand to certain depth under the footing; this technique aims to reduce the settlement and increase bearing capacity. So the second technique is more expensive than first technique. Consequently, the principle target of this paper is to investigate and compare the character modification of the bearing capacity considering settlement reduction through using both local soil replacements of soft clay soil and sand columns reinforcement which not covered in previous researches.

2. GENERAL FINITE ELEMENT MODELING DETAILS.

2.1 THE MARTIALS USED TO MODEL FINITE ELEMENT.

Finite element (FE) techniques have been utilized as a part of most geotechnical building to assess complex issues. 3D modeling can mimic field conditions legitimately while conventional analysis is time wasting and complicated, in addition using the laboratory models need more effort and budget. In this search the PLAXIS 3D foundation version 2013 was chosen, this finite element software is created in the Delf technical university.

In finite element models, the same models are fabricated as that constructed for both soil replacement and the group sand column in the site. The dimensions (depth and width) of the numerical models were chosen as enough so that it simulates the field model. The standard boundary option in the program is selected, where this boundary option makes movement in the top surface free. If considering the model boundary in yz-plane, displacements in the x directions are fixed to zero while in the y and z directions the displacements are free. The bottom boundary is fixed in all directions. The generated mesh was selected medium and it was refined in the zone of reinforcement, because both stresses and displacements are higher in this zone, in addition, the program refines these zone automatically.

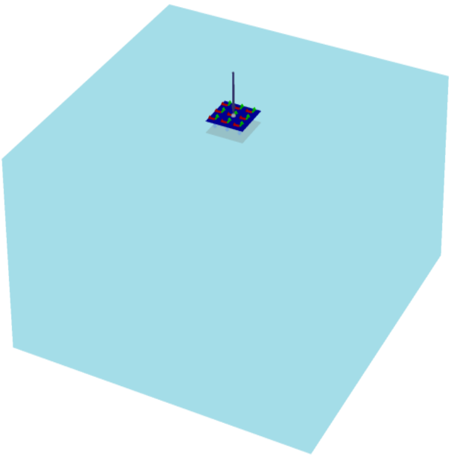
Materials of the soil profile and the used sand were depicted by the criteria of linear elastic-perfectly plastic Mohr-Coulomb. Five input parameters needs to create the model; “Young's modulus of elasticity (E) as the basic stiffness parameter, Poisson’s ratio (υ), internal friction angle (φ), cohesion (c) and dilatancy angle (ψ)”. The clay layer in this study was dry. Hence, there was no need to enter ground water level and a drained condition was liked in the analyses. The foundation was modelled as a plate element which is defined by thickness (d), unit weight of material and stiffness (E). The program recommends subtracting half the unit weight of the soil from the unit weight of the footing. This subtracting is to account for soil-concrete interaction and depends on the contacted area of concrete with the soil. So the unit weights were taken as 16.25 kN/m^3. Table (1) summarize the material parameters utilized for soil and sand.

Table1 Parameters of finite element model input.

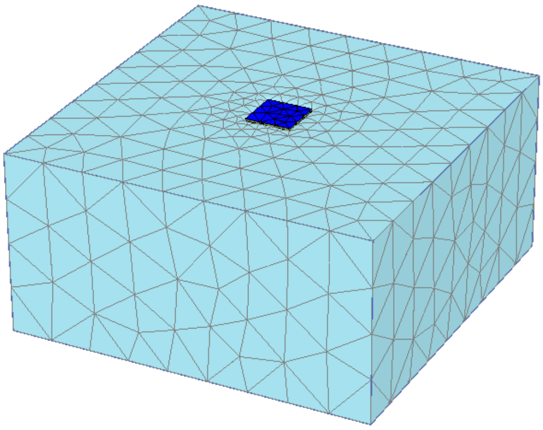
Material property	**“Material type”**		**“Structural elements”**
	clay	**sand**	
Type	“Mohr coulomb – drained”	“Mohr coulomb – drained”	“Linear, isotropic”
γ_{usat} (kN/m^3)	14	20	-
γ_{sat} (kN/m^3)	16	22	-
γ	-	-	16.25
E' (kN/m^2)	5000	50000	23.5E^6
E_{oed} (kN/m^2)	10710	72000	-
c' (kN/m^2)	5	0	-
Ø'	20	40	-
Ψ	o	5	-
ν'	0.4	0.25	0.15
d (m)	-	-	0.45

2.2 UNTREATED CLAY SOIL MODEL.

The finite element model of untreated clay soil is shown in Fig. 1, which consists of soil volume 20 × 20m plan area and 10m in depth. 2.5 × 2.5m rigid concrete footing with 0.45m thickness was modelled on the top of soft clay. The interface elements between the footing and soft clay has been utilized to consider as footing-soil interaction. About 5000, 15 node triangular elements were taken to generate the mesh of the soil and footing. The maximum settlements under footing were taken using progressive concentrated loads until reaching to failure load. These settlements were considered as reference points to evaluate the soil improvement techniques.



(a)



(b)

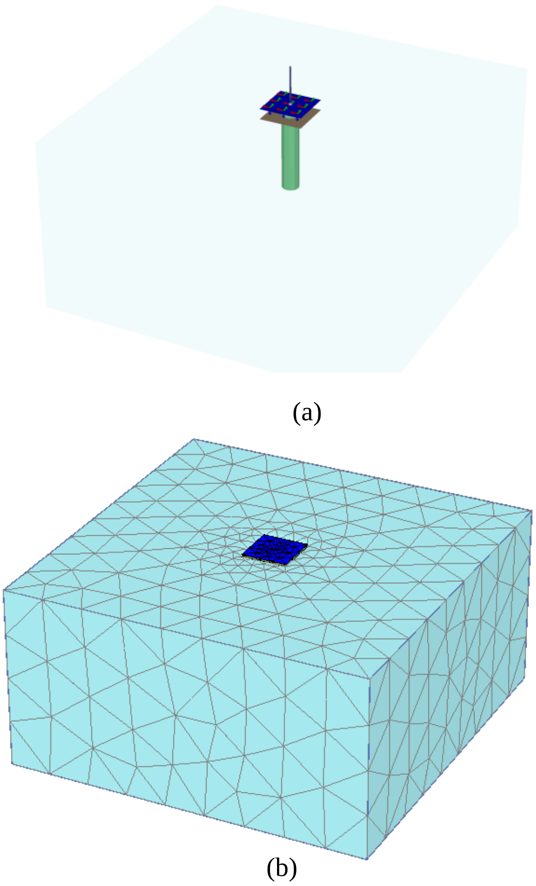
Fig. 1 (a) Input geometry of the untreated model in PLAXIS 3D (b) Generated meshes.

2.3 TYPE OF SOIL IMPROVEMENT.

This paper gives an overview of two techniques that are used to enhance the performance of the soft clay in situ. Both techniques were carried out by adding sand soil to the soft clay using finite element analyses, and the column loads were applied progressively then the settlements were recorded. The two techniques can be summarized as following:

2.3.1 SAND COLUMNS TECHNIQUE.

The sand columns are constructed from compacted coarse sand in the site vertically to improve the performance of soft or weak soils. Compaction of the sand particles can be done by impact methods, such as with a falling weight or an impact compactor machines. Presenting stiff granular columns of thickly compacted, coarse, granular backfill into the local soil generously enhances the shear strength and settlement attributes of the soft clay [9]. A 3D finite element models were used to represent the clay soil after improvement by sand columns. The finite element models were created from 2.5 × 2.5m rigid concrete footing with 0.45m thickness resting on sand columns. The sand columns were modeled in Plaxis program by adding cylinders to confine certain volumes from clay soil then the confined volumes changed to sand properties. The diameters of sand columns after deleting walls of the cylinders are 0.5m and extended to 5m depth inside clay soil, the sand columns are considering floating columns. An interface elements between the footing and soft clay has been used to consider the footing-soil interaction. Depending on the materials properties shown in table 1, the model of concrete footing resting on single sand column is presented in Fig. 2 which is the first case of clay soil improvement using sand columns.



(a)

(b)

Fig. 2 (a) Finite element model (b) generated meshes of footing resting on single sand column.

The second case is the modeling of reinforced soil by two sand columns with spacing between centers of the sand columns is 3d (where d is the diameter of sand column). Fig. 3 shows the finite element model for two sand columns by 5000 node triangular elements for soil and footing. For footing-soil interaction, the interfaces elements between the footing and soft clay has been added. Balaam and Booker (1981) [12] explained the radius of influence (Re) to the actual column spacing by the relation Re = c.S, where S is the actual spacing (from center to center of the columns) and c is a constant having values of 0.525 and 0.564 for triangular and square patterns, respectively. For most practical cases, the diameter of influence may be assumed to be equal to the actual column spacing.

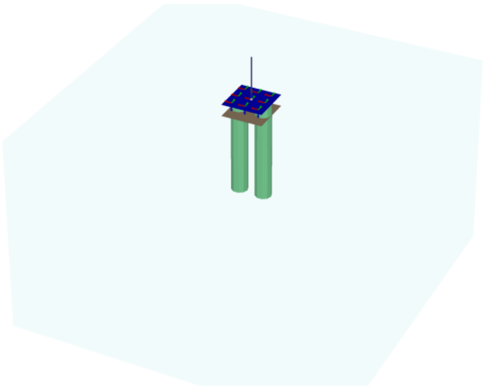


Fig. 3 Finite element model for footing resting on two sand columns.

The third case is group of 4 sand columns with spacing between centers of the sand columns is 3d. The finite element model for 4 sand columns is shown in Fig. 4 by 5000 node triangular elements for soil. Analyses the modeling of reinforced soil by four sand columns were conducted by adding interface elements between the footing and soft clay.

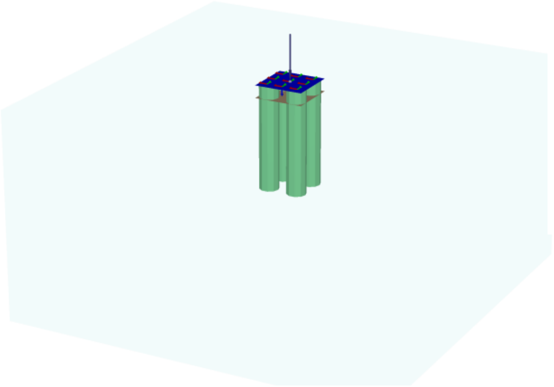


Fig. 4 Finite element model for footing resting on four sand columns.

2.3.3 SOIL REPLACEMENT TECHNIQUE.

The replacement of weak soil is most applicable and economically, it commonly used in soft cohesive soils as other soils. “The bearing capacity of footings on soft clay can be also enhanced considerably by placing a layer of compacted granular fill of limited thickness without/with geotextile or geogrid reinforcement at sand clay interface” [8]. Replacement of weak soil is considering simplest and oldest methods which improve the bearing soil conditions. The foundation state can be modified by replacing poor soil (eg. medium or soft clay and organic soils) with more competent materials. The competent materials are sand, gravel or crushed stone as well, nearly any soil can be used in fills. Also there some soils are more difficult to compact than others when used as a replacement layer [10].

A 3D finite element models were used to represent the clay soil after improvement by sand layer. The finite element models were created from 2.5 × 2.5m rigid concrete footing with 0.45m thickness resting on compacted sand layers underlain by soft clay. The sand layers were modeled in Plaxis program by creating volumes under the footing and changing these volumes to sand by using properties of sand shown in table 1. Two case of the improvement were used, the first case use a layer of compacted sand with 1m thickness and the second is 1.5m in thickness. The models of concrete footings resting on compacted sand layers with thicknesses of 1m and 1.5m are presented in f Figs. 5 and 6. Fig. 7 shows 5000 node triangular elements of soil and footing finite element model for improvement of soft clay with sand layer 1m in thickness.

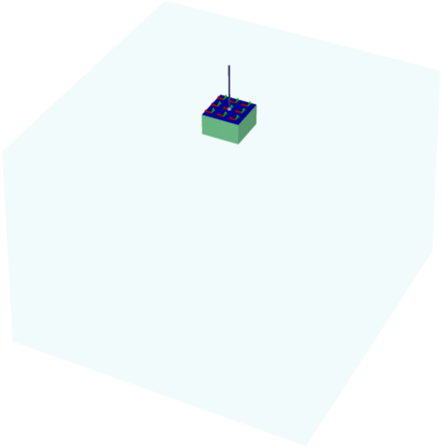


Fig. 5 Finite element model for footing resting on compacted sand layers with thicknesses of 1m.

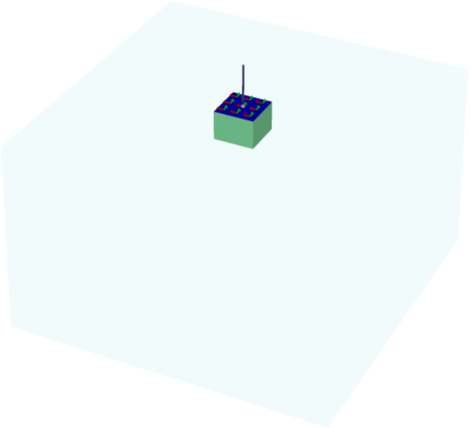


Fig. 6 Finite element model for footing resting on compacted sand layers with thicknesses of 1.5m.

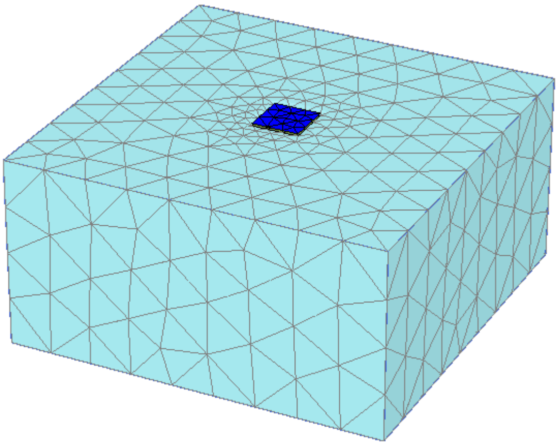


Fig. 7 generated meshes of footing resting on compacted sand layers with thicknesses of 1.5m

2.4 THE SETTLEMENT CALCULATIONS.

The settlement results from PLAXIS 3D Foundation for treated soft clay by floating stone columns or by replacement method is compared with the settlement of untreated soft clay.

The settlement performance is evaluated using a settlement improvement factor, n, which was developed by Priebe (1995) [13]. The factor of settlement improvement, n, is defined as the ratio of the settlement of an untreated footing to that of a treated footing. The settlements were recorded at end of the final calculation phases in Plaxis program.

In case of soil replacement, the settlement results obtained from the software were contrast to Janbu equations for evaluating the average settlement of flexible foundations on saturated clay soils.

Janbu et al. (1956) proposed an equation for assessing the average settlement of flexible foundations on saturated clay soils. This equation is [14]:

$$S_e = A_1 A_2 \frac{q_o B}{E_s} \qquad (1)$$

Where A_1 is a function of H/B and L/B and A_2 is a function of D_f/B , these values can be concluded from Fig. 8.

q_o is the applied load on footing, E_s is the modulus of elasticity for clay soil and B is the width of footing.

If there should be an occurrence of floating sand columns, the results of settlement which obtained from the Plaxis software were contrasted with Brom's analytical equations. When the load is applied on soft soil and columns, two settlements are calculated and compared, column settlement (S1) and soil settlement (S_2). The calculation of settlements can be depicted from equations 2 to 4 [2]:

$$S_1 = \sum \frac{\Delta h}{a} . \frac{q_1}{E_{column}} \qquad (2)$$

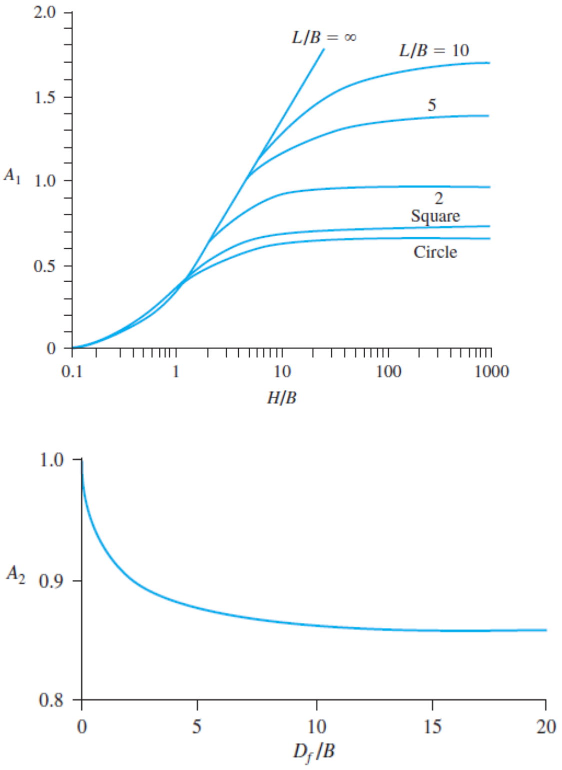


Fig. 8 A_1 and A_2 Values for calculation of elastic settlement (after Das, 2011)

S_1: "Settlement of column", m
Δh: "Thickness of layer", m
q_1: "Load on columns, kPa".

E_{column}: "Young's modulus of column, kPa".

$$a = \frac{A_c}{A_t}$$

A_c = "Total area of columns".
A_t = "Total area of improved soil".

$$S_2 = \sum \frac{\Delta h}{1 - a} . \frac{q_2}{E_{soil}} \qquad (3)$$

Where:
S_2: "Settlement of soft soil, m".
q_2: "Load on columns, kPa".
E_{soil}: "Compression modulus of unimproved soil, kPa".

The deformation of sand columns and soft soil relates on properties of each one, absolutely two spread conditions present as following:

1. If suppose that q1 = q_{max}, column settlement (S_1) is compared to soil settlement (S_2) as the following:

When $S_1 > S_2$, in same time the load on columns (q_1) is reduced gradually while the load on soft soil (q_2) is increased, therefore S_1=S_2. Then, the estimated S_m is equal to S_1 and S_2. So S_m can be calculated from equation (4):

$$S_m = S_1 = S_2 = \sum \frac{\Delta h . q}{a . E_{column} + (1 - a) E_{soil}} \qquad (4)$$

The Settlement at enhanced mass is equal to S_1 and S_2.

2. When $S_1 < S_2$ at that point column can't stand any more load and afterward the settlement S_m which happens is equivalent to the computed settlement S2 in unsterilized soil.

3. The Results and Discussion.

The main aim of this study is to find out the effect of compacted sand columns and shallow sand layers on the settlement under concrete footings. Maximum settlement for each case was measured. Fig. 9 illustrates pressure-settlement behaviour of improved soft clay by replacing 1m and 1.5m of the soft clay with compacted sand layers.

The simulations results explain the extreme vertical settlement at center of the foundation equals to 278.021mm in resistance pressure of 225 kPa. The maximum vertical settlement in the foundation center for improved soil with 1m thickness was 304.534 mm in resistance pressure of 350 kPa. In case of improved soil with 1.5m thickness sand, the maximum vertical settlement in the foundation center was 229.78 mm in resistance pressure approximately 350 kPa.

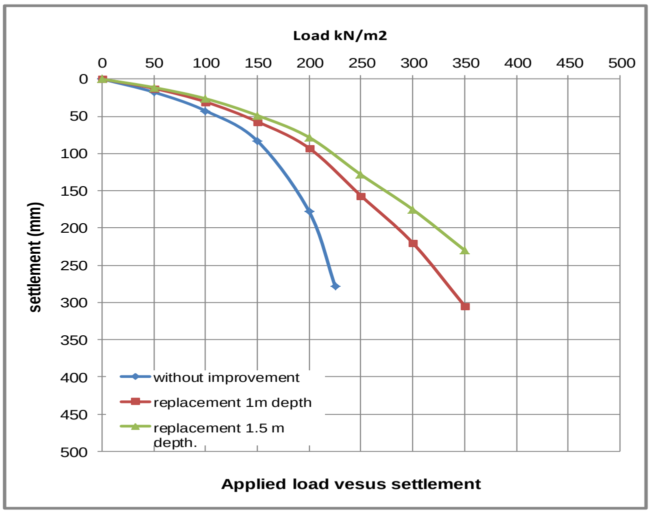


Fig. 9 pressure-settlement behaviour of unimproved soft clay and improved with 1m and 1.5 m compacted sand.

Fig. 10 demonstrates a standard relationship of vertical pressure versus vertical settlement of the foundation at center point rested on compacted sand columns. In case of single column, the maximum vertical settlement at the foundation center is 1000.116 mm in approximately 300 kPa resistance pressure load. Using two columns, the maximum vertical settlement in the foundation center was 359.309 mm in approximately 300 kPa resistance pressure loads.
In case of three columns, the maximum vertical settlement in the foundation center was 308.9 mm in resistance pressure load approximately was 350 kPa.

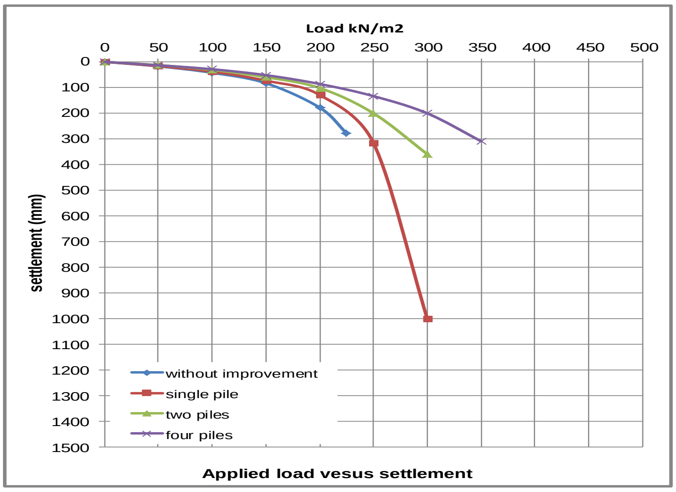


Fig. 10 pressure-settlement behaviour of unimproved soft clay and improved using compacted sand columns.

4. THE SETTLEMENT IMPROVEMENT FACTOR.

To distinguish the reduction in the settlement after improving the soft clay, the settlement improvement factors, n, were used. Fig. 11 shows the settlement improvement factors versus various applied pressures for soft clay improved with 1m and 1.5 m compacted sand layers. In pressure load of 225 kPa for improved with 1m and 1.5 m compacted sand, the maximum vertical settlements were 124.7745 mm and 103.3455 mm, so the settlement improvement factors are 2.22 and 2.69 respectively.

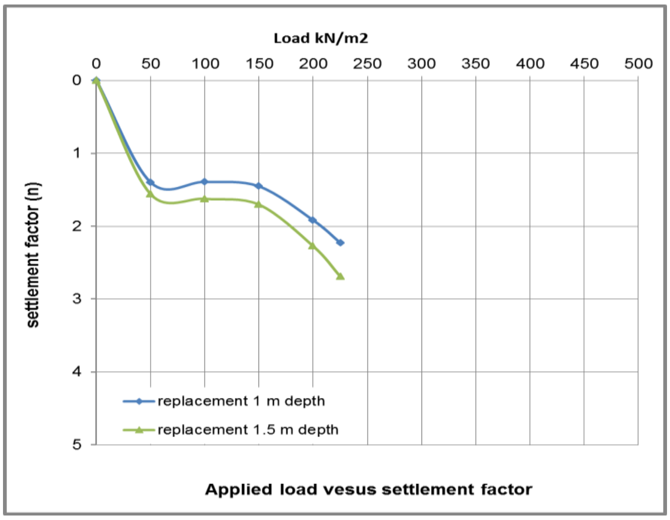


Fig. 11 settlement factors versus the pressure for improving using 1m and 1.5 m sand layers.

Fig. 12 shows the settlement improvement factor versus various applied pressures for improved soft clay using compacted sand columns. In pressure load of 225 kPa for improved using single column, two columns and four columns, the maximum vertical settlements were 222.29mm, 151.071mm and 109.788mm, so the settlement improvement factors are 1.25, 1.84 and 2.53 respectively.

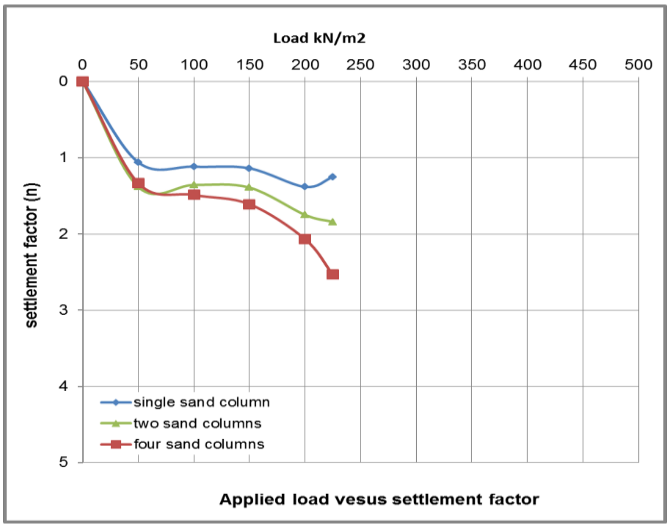


Fig. 12 settlement factors versus the pressure for improving using compacted sand columns.

It has been observed that the settlement improvement factor increases with increasing the thickness of replaced layer and also it increase with increasing the number of sand columns.
Fig. 13 shows the settlement factor versus the pressure on footing for all improvement techniques. It can be concluded that use the replacement technique under the loaded area is effective in reducing the settlement factor. Manar et al, (2012) [15] concluded that “use of replacement soil under shallow

foundation can reduce consolidation settlement and increase soil bearing capacity. It has some advantages over other techniques and deep foundation as it is more economical and requires less delay to construction".
Use of compacted sand columns settlement needs to use four columns and more depending on the applied load. Use of sand columns less than four decrease the settlement slightly.

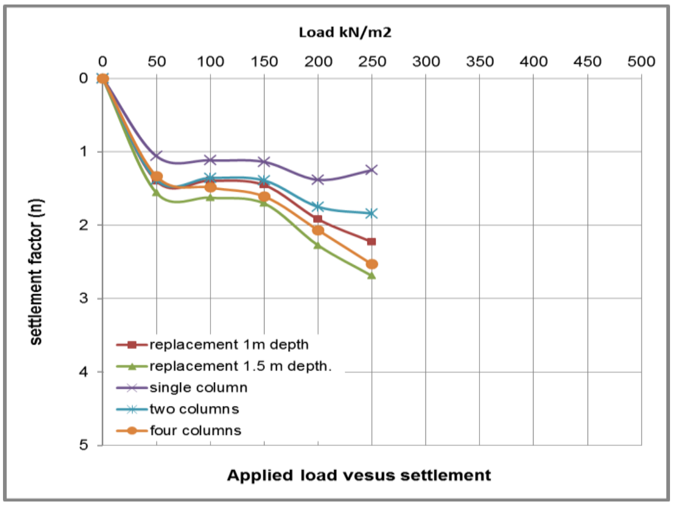


Fig. 13 settlement factors versus the pressure for all improvement techniques.

Black et al, 2007 observed that when a load is applied, a granular column develops end-bearing resistance and side friction similar to that of a pile. However, the column is non-rigid element, so it may bulge laterally into the surrounding soil. A composite soil – granular column system is formed in which the surrounding soil provides lateral support to the column, preventing expansion under load. The increased lateral stresses within the clay lead to further consolidation and enhanced resistance to column bulging. This process continues until equilibrium is reached .

5. FINITE ELEMENT & ANALYTICAL SETTLEMENT COMPARISON.

In this section a comparisons between the results of finite element with analytical methods are conducted. Two analytical methods based on Janbu's equations and Broom's assumptions are compared with FFE results. In case of soil replacement, the settlement results from the software were contrasted to Janbu equations for evaluating the average settlement of flexible foundations on saturated clay soils. In floating sand columns, the results of settlement from the plaxis models and Brom's analytical equations were compared.

In comparison between FE & Janbu analytical methods results for improving using 1m and 1.5 m compacted sand layers, based on Fig. 14 there are huge deviation between the FEM results and analytical methods results. The results obtained from FEM are significantly more than that obtained from analytical methods when the loads are greater than 150 kN/m^2.

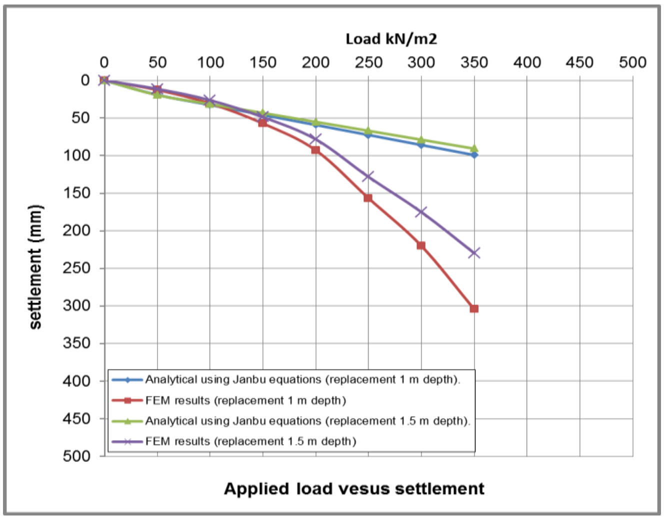


Fig. 14 Finite element & analytical settlement comparison for improving using 1m and 1.5 m sand layers.

Fig. 15 shows the relations between the FEM results and analytical methods for improving using compacted sand columns. In case of floating sand piles a few dissimilarity were observed between FEM method and analytical methods. The results were concordant when the loads less than 250 kN/m^2. The results obtained from FEM are significantly more than that obtained from analytical methods when the loads more than 250 kN/m^2.

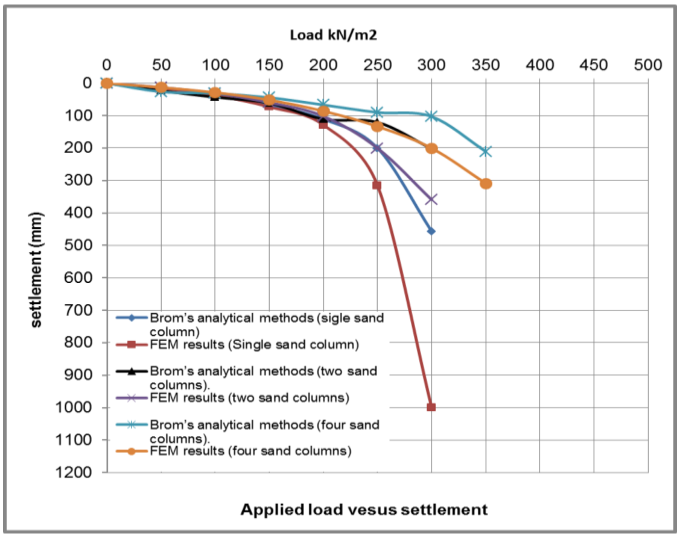


Fig.re 15 Finite element & analytical settlement comparison for improving using compacted sand columns.

6. THE CONCLUSIONS.

Groups of numerical examination were completed to assess the settlement of shallow foundation rested on soft clay improved using sand replacement technique or a group of compacted sand columns. The factor of settlement improvement, n, which is defined as the ratio of the settlement of an untreated footing to the settlement of a treated footing were used to evaluate the reduction in settlement after improvement.

It may be concluded from the obtained results that the stress-settlement behaviour increases with increasing the thickness of sand layer. Increasing the thickness of replaced soft clay with compacted sand layer evidently decreases the settlement and increases the resistance stress. It can be concluded that use the replacement technique under the loaded area is effective in reducing the settlement factor. In certain pressure load (225 kPa) for improved with 1m and 1.5 m compacted sand, the settlement improvement factors are 2.22 and 2.69 respectively.

Using the sand columns technique reduces the settlement in different proportion depending on the number of sand columns and the value of applied pressure. In pressure load of 225 kPa for improving using single columns, two columns and four columns, the settlement improvement factors are 1.25, 1.84 and 2.53 respectively. Use of compacted sand columns to decrease the settlement needs to use four columns and more depending on the applied load. Use of sand columns less than four slightly decrease the settlement.

In comparison between FE & Janbu analytical methods results results for improved with 1m and 1.5 m compacted sand, the results showed that there are evident deviation between the results of FEM and analytical methods when the loads are greater than150 kN/m^2.

The results of sand columns show a insignificant differences between FEM analysis and analytical methods, the analyses results of FEM seem significantly more than that obtained from analytical methods when the loads more than 250 kN/m^2 and are compatible when the loads less than 250 k/m^2.

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