Improvement of Soft Clay Soil Using Stone Columns

Kamal Mohamed Hafez [1], Walid Hamdy El Kamash[1], Azza Hassan Moubarak[2], Mohamed Ahmed Kasem[3]

[1] Professor, Geotechnical and Foundation Engineering Department, Faculty of Engineering, Suez Canal University, Ismailia, Egypt., [2] Associate Professor Civil Department, Faculty of Engineering, Suez Canal University, Ismailia, Egypt., [3] MCs candidate Civil Engineering Department, High Institute of Engineering and Technology, El-Arish City, North Sinai, Egypt.

1. Abstract

In this paper presents a comprehensive numerical investigation on different parameters that affect the design of stone columns. The stone column has been known as a useful technique to improve weak soils. A new planned city is in the south of Port Fouad - Governorate Port Said, Egypt. Its residential buildings will be constructed on a raft. The main soil stratification at the site is soft soil deposits. Generally, soft soil deposits have a weak bearing capacity and excessive settlement characteristics. Before beginning any construction activities, it is important to improve the current soft soil to avoid these problems. It was suggested to stabilize the soil of the new city with stone columns. Finite-element analyses have been performed using PLAXIS 3D V.20 software. The effective parameters studied are the ratio of the Length of stone columns to soft soil height L/H, the ratio of the diameter of stone columns to its length D/L, the distribution pattern, centroid spacing between stone columns, Cushion soil thickness, and Compression index of soft clay. The investigation recommends suitable cost-effective parameters for the design of stone columns in the studied site.

2. Keyword

Stone column, Plaxis 3D, Numerical Modelling, Improve soft clay, Port-Said.

3. Introduction

Occasionally, New Port Said city were constructed in areas having thick layers of soft clay deposits. These deposits possess low shear strength and high voids ratio, which lead to excessive settlements even if subjected to low or moderate surface loads. Soft clays are regarded as difficult soils for foundation purposes because of this. To overcome and improve such clay, several improvement techniques have been used. One of the most often used methods employed worldwide is the improvement of soft clay deposits using stone columns (SC) [1]. Stone columns increase the overall strength and stiffness of compressible soft clay deposits, but also promote effective drainage surrounding that make acceleration the consolidation process of the clay. However, when exposed to compressive stresses, stone columns may fail for many reasons, including bulging or punching [2,3]. To estimate the bearing capacity and settlement of foundations resting on soils reinforced by stone columns, several researchers developed theoretical solutions [3,4]. Ambily and Gandhi carried out both experimental and finite-element analyses to study the effect of shear strength of soil, angle of internal friction of stones, and spacing between the stone columns on the behavior of stone columns [5]. While Das and Pal improved the Soft and Loose soil Layers using the stone column technique. Stone columns are put into soft soil as compacted columns of gravel or crushed rock. Sometimes referred to as composite ground, the earth is enhanced by compacted columns [6]. The most common construction method is Vibro – Replacement Method or Vibro – Displacement Method as called by some people are placed using Vibro, which involves driving a specially designed vibrating tube into the ground. As the tube is driven below, the earth is moved. There is a top-loading hopper on the tube. Crushed stone is placed into the hopper after the necessary depth is reached, and as the tube is drained, the stone replaces the soil. The stone is then compacted by gradually inserting the tube into it [7]. Castro demonstrated some of the effects of column placement such as increased pore water pressure and horizontal stresses, and vibrator penetration remolding of the surrounding soil. However, it is difficult to derive findings that can be used for crushed stone column design based on these measurements, because the measurements relate to particular cases and cannot be generalized in a straightforward way [8]. The presence of stone column results in a composite material that is higher in shear resistance than in-situ soil and has lower overall compressibility. Thus, stiffness of the stone, is provided by the lateral stress within the weak soil. When axial load is applied at the top of a single stone column, an enlargement of the column diameter is produced beneath the surface. This enlargement, in turn, increases the lateral stress within the clay which provides additional confinement for the stone column. An equilibrium state is eventually reached, resulting in a reduction in the vertical displacement, when compared with the untreated ground [9]. The effect of stone columns on stress concentration ratio (n) was Studied. (n) increased as the clay layer compression index increased and decreased as the area replacement ratio increased [10]. Numerically lateral expansion of stone columns was studied in two cases: floating and end bearing columns. They found that maximum lateral expansion takes place at the end of some floating columns. Generally, in the most studied models, the maximum lateral expansion took place at a depth of 0.4d [11]. In soft soil conditions, the loss of infill material in the surrounding soil renders the granular columns effectiveness. Where the soil may enter the voids of the granular material, thereby clogging the granular columns which lead to a reduction in permeability of these columns. Encasing the stone columns with suitable geosynthetic material can solve these issues as this encasement provides additional lateral confinement and also acts as a barrier between the soft soil and the granular material [12].

In this study, numerical study of a social housing project in Port Fouad, Egypt, which concentrated on soft soil improved with stone columns. Finite-element analyses have been performed using PLAXIS 3D V.20 software. Hardening soil and Modified Cam Clay models are used to simulate soft soil. The modeling was verified with published numerical studies. The effective parameters studied are the ratio of the Length of stone columns to soft soil height L/H, the ratio of the diameter of stone columns to its length D/L, the distribution pattern, centroid spacing between stone columns, Cushion soil thickness, and Compression index of soft clay. Numerical results were compared with published analytical analysis settlement. The conducted site investigation revealed that the soil profile consisted mainly of soft clay to a great depth, with some separation of a silty sand layer with an average thickness of 5 m starting at a depth greater than 7 m. The sand layer was thin or nonexistent in some locations, particularly on one side of the site, where soft clay extended from the surface to a depth of 45 m.

4. Verification of the Numerical Model

Finite Element Method has been applied to Geotechnical Engineering problems since 1960 [13]. In the following study, the finite element program of PLAXIS 3D V.20 is utilized for investigating the improvement of soft clay soil using stone columns. The numerical modeling has been validated using study of Hasan and Samadhiya, 2016. The researchers studied the behavior of floating stone columns in clay. Soft clay and stone column were modeled using Mohr-Coulomb. The researchers idealized the floating stone in clay as a unit cell with as shown in Fig.1. The relationship between load and settlement is verification as shown in Fig 2. Fig 2 shows good agreement of the analyzed load settlement with Hassan 2016 [14].

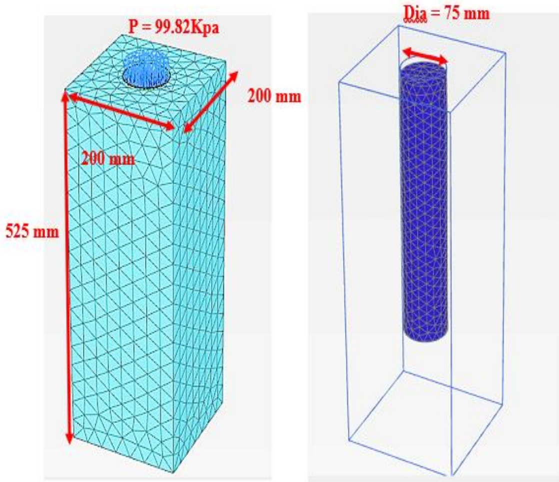


Fig. 1 Floating stone column modelling of unit cell of Hasan & Samadhiya,2016

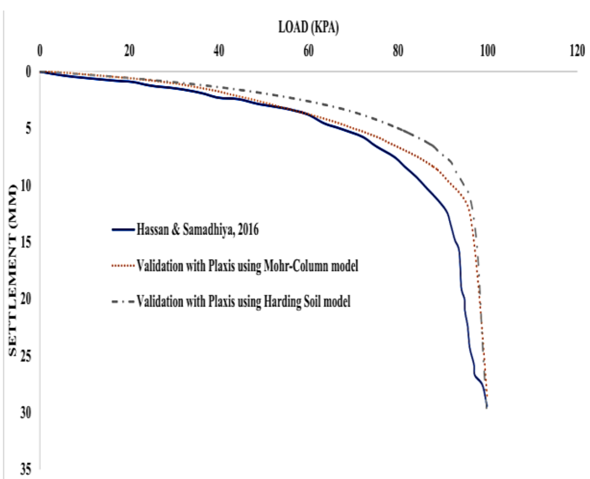


Fig. 2 Verification with Hasan & Samadhiya, 2016

5. Numerical Analysis

The planned new city has a surface of 125 acres. 48 residential buildings are contained in planned city. Each building consists of ground floor and 5 typical floors. All floors were constructed using reinforced concrete skeleton system supported on raft foundation. Raft dimension are 28 × 20 m2 and 1m thickness. 100 kPa load is applied on the raft. The soil stratification at the site of the buildings consists of soft silty clay from ground surface down to depth of 5.0 m, followed by sand/silty sand up to depth of 13.0m. Then, there is a lower soft clay layer down to the end of boring at 45.0 m. The groundwater level is 1 m below the ground surface. It was suggested to stabilize the soil adapting stone column. The constructed stone columns are of depth H = 6 m with a nominal diameter D of 1.0 m and arranged in an equilateral triangular pattern with spacing 2.15D. 1.0 m granular cushion is proposed below the raft and stone columns starts directly below the cushion. The arrangement of stone columns under raft is shown in Fig 3. Fig 4 shows the soil layers with stone columns with dimensions in meters. The object of this study is to conduct parametric study considering different factors that affect the design of stone columns.

Since the raft dimension is 28 × 20 m2, to eliminate the effective boundary the model dimension has to spaced 5B from the raft boundary. Then, the model dimension is 140 × 100 m2. The model depth is the same with bore hole depth of 45m. Plaxis 3D generated mesh with options for global and local mesh refinement. Plaxis provides several options of mesh density ranging from very coarse to very fine mesh. Mesh size was chosen to model the soil deposit. Mesh was then refined in the soil area surrounding the stone columns as shown in

Figs.5. Refine mesh generation at vertical sec x-x at (0,0) is shown in Fig.6.

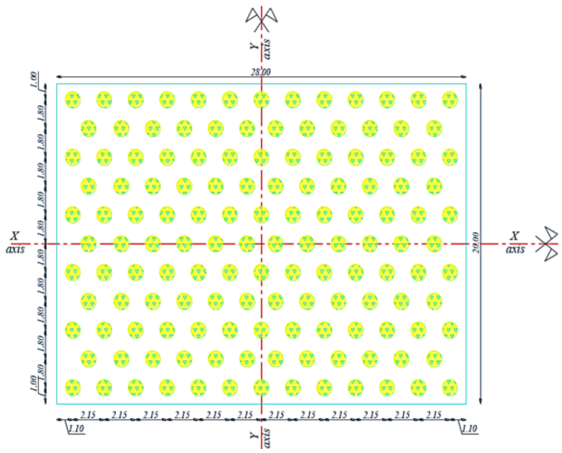


Fig. 3 Stone column distribution patterns

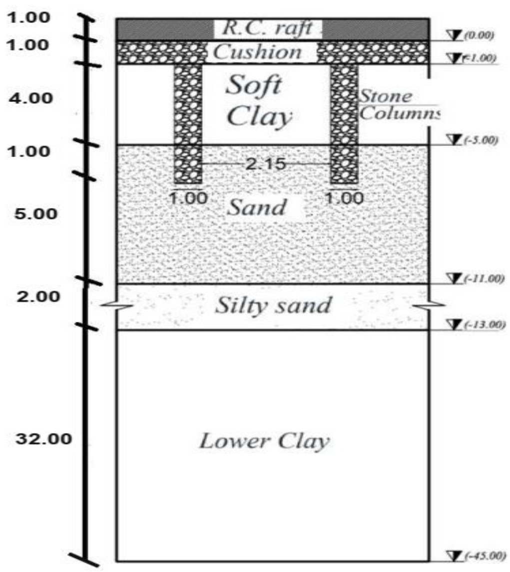


Fig. 4 Soil Profile of Stone column with soil layers with dimensions in meters

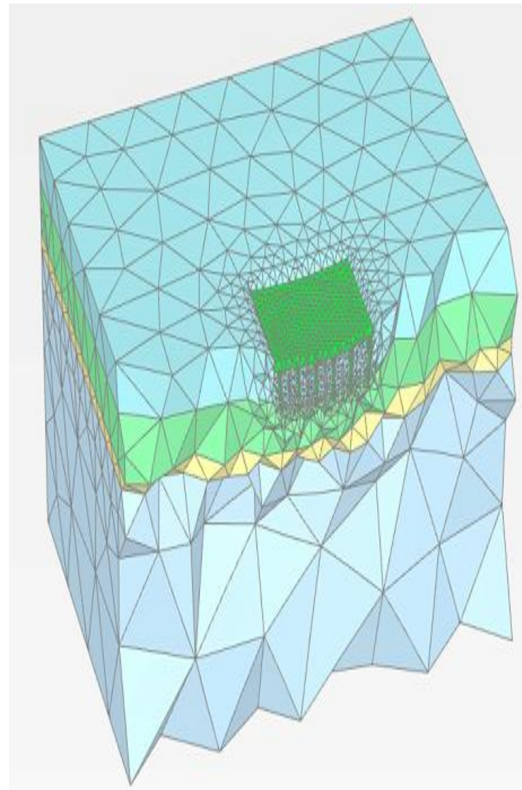


Fig. 5 Mesh generation

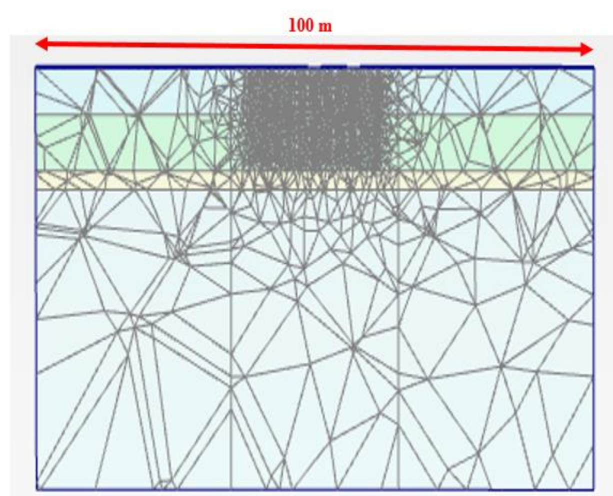


Fig. 6 Refine mesh generation at vertical sec x-x at (0,0)

In this study, Modified Cam-Clay model is used to define soft clay layers. Mohar Column Model is used to define Stone columns and sand layer. Raft is defined with liner model. The material properties are shown in Tables 1.

6. Parametric Study

The objective in this study is to conduct parametric study considering different factors that affect the design of stone columns. These parameters are the most effective in stone column behavior. The variables are ratio of length of stone column to soft layer depth (L/H) where, ratio of diameter of stone column to length of stone column (D/L), stone columns pattern, stone columns Spacing (S), cushion thickness ratio to the length of stone column ($t_{cushion}$ / L) and compression index (Cc). Ranges of the variables are shown in Table 2.

Table 1 Soil properties.

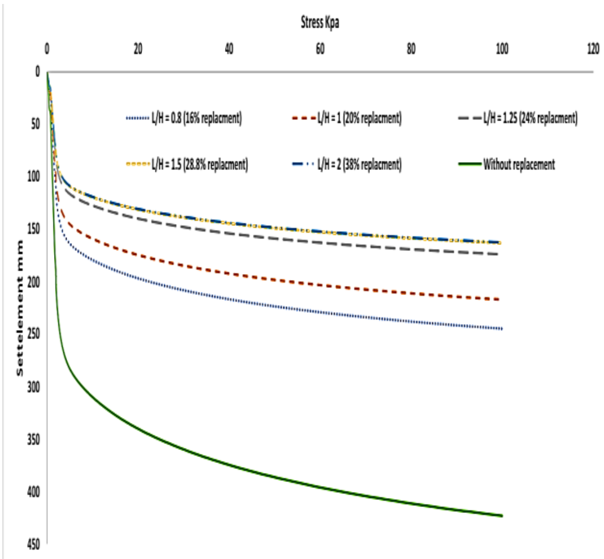
Layer	γ_{sat} (kN/m^3)	C_c	E (MPa)	κ	λ	M	N	P_c	e_Γ	φ (°)
Topsoil crest	15.0	–	–							–
Soft clay	16.0	0.5	–	0.04	0.22	0.888	0.4	105	3.27	–
medium to lose silty sand	17.0	–	30							35
Medium clay	17.2	0.4	13.5	0.03	0.17	0.888	0.45	150	3.3	–
Stone column	16.7	–	48							44

Table 2 Ranges of the variables in the parametric study

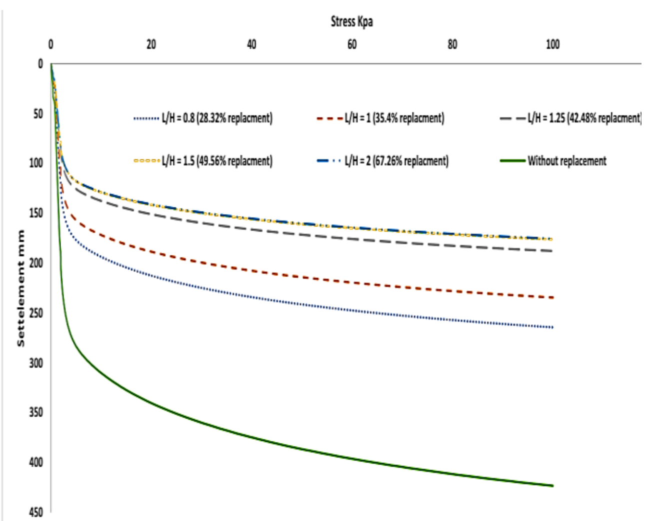
No.	Variables	*Ranges*
1	L/H	0.8, 1, 1.25, 1.5 and 2
2	D/L	0.125, 0.133, 0.15 and 0.166
3	Stone column Pattern	Triangular, Rectangle and Hexagonal
4	Stone column Spacing (S)	2D, 2.15D, 2.3D, 2.5D, 2.75D and 3D
5	$t_{cushion}$ / L	0, 0125, 0.166, 0.2 and 0.25
6	Cc of lower clay layer	0.4, 0.5, 0.6, 0.7 and 0.8

6.1. Effect of (L/H) on soil settlement.

The effect of (L/H) ratio for stone column on soil settlement was studied considering the following construction case. Column diameters are 1m, the pattern distribution is triangular with spacing of 2.15D and 1m soil cushion above the stone columns. The studied (L/H) are 0.8, 1, 1.25, 1.5 and 2. Column diameter of 0.75 m were also considered. Figs 7 a and b show the settlement – stress relations for stone column diameters of 1m and 0.75m, respectively. From the two figures, it can be seen that the settlement decreases by improving the soil. Settlement for untreated soil is 420 mm at 100 kPa applied load on raft. While as, when (L/H) = 0.8, the settlements are 244.7 mm and 264.276 mm for 1m and 0.75 m diameters, respectively. (L/H) =1 implies that stone column is supported on sand layer. That is, it`s end bearing. There is considerable different in soil settlement for cases (L/H) from 0.8 to 1 & from 1 to 1.25. This different is due to the stone column changing from floating case to end bearing case. Fig 8 shows a comparison of settlement for columns diameters 1m & 0.75 m, at different (L/H) ratios. As seen from the figure, settlement is improved considerably for (L/H) $\geq$ 1.25 as (L/H) $\leq$ 1.25 minor improvement is achieved. Hence, it`s reach to adapt (L/H) = 1.25 for this site. The difference of settlement between the two diameter 1 and 0.75 m is not that signified. However, it should be mentioned that the columns patterens spacing in this analysis is 2.15D. That is the spacing decrease as the diameter descrease.



a



b.

Fig. 7 Stress – settlement curves for different L/H ratios under raft load 100kPa a) D=1 m & b) D=0.75 m

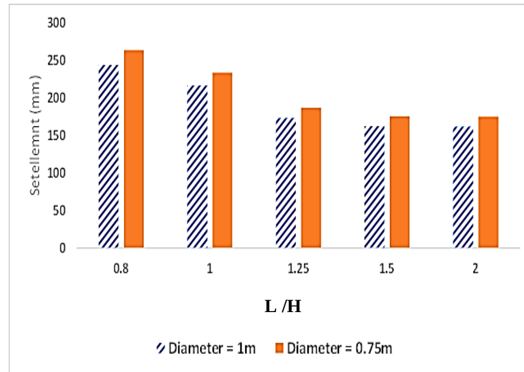


Fig. 8 Settlement for different L/H ratios (D= 1m & D = 0.75 m).

6.2. Effect of (D/L) on Soil Settlement.

The effect of (D/L) ratio for stone column on soil settlement was carried out for the following construction case. Column length is 6m, the pattern distribution is triangular with spacing of 2.15D and 1m soil cushion above the stone columns. Fig 9 shows the settlement – stress relations for (D/L) ratios. From the figure, it can be seen that the settlement decreases by improving the soil. Settlement for untreated soil is 420 mm at 100 kPa applied load on raft. At (D/L) = 0.125, the settlement is 190.2 mm, and at (D/L) = 0.166, the settlement is 173.85 mm. Also, it is noticed that increasing (D/L) from 0.125 to 0.166 the improvement of settlement changes from 55.44% to 58.91%.

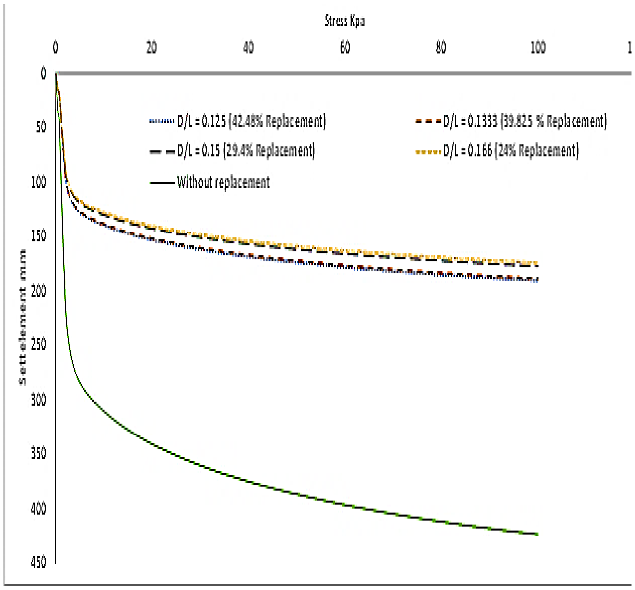


Fig. 9 Stress – settlement curves for different D/L

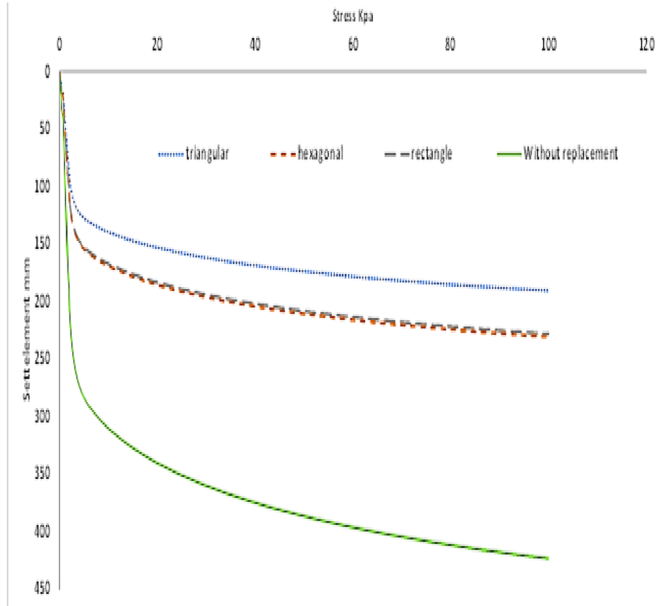


Fig. 10 Stress – settlement curves for stone columns pattern

6.3. Effect of Stone Column Pattern on Soil Settlement.

Stone columns pattern are triangular, rectangle, and hexagonal. The effect of stone column pattern is studied for the following case (D/L) = 0.1666, (L/H) = 1.25, (S) = 2.15D and 1m soil cushion. Fig. 10 shows that triangular pattern gives the least settlement than rectangle, and hexagonal patterns. Settlement of triangular pattern is 173.8495 mm at 100 kPa. While settlement of rectangle and hexagonal patterns are 227.9mm and 230.2mm, respectively at the same load. Soil replacement percentage of triangular, rectangle, and hexagonal patterns are 24%, 22%, and 19%. That is triangular presents the most economical solution among these patterns. It gives the densest packing.

6.4. Effect of (S) on Soil Settlement.

Usually, column spacing range from 2 to 3 times the diameter of the column. Spacing is depending upon the site conditions, loading pattern, column factors, the installation technique, and settlement tolerances. The effect of stone column spacing is studied for the following case (D/L) = 0.1666, (L/H) = 1.25, triangular pattern and 1m soil cushion. Fig.11 shows the settlement curves for columns spacing ratio (S) for 2-3 diameter. From the Fig 11, it can be seen that the soil settlement is improved considerably with the decrease of columns spacing. More sound effect results when S < 2.75 D. Soil settlements are 298.6 mm at spacing 3D and 248.7 mm at spacing 2.75D. Replacement ratio “as” and improvement of soil settlement “is” at 100 kPa were calculated according to the following equations.

$$as = \frac{\sum a_C}{A_{raft}} \quad (1)$$

$$is = \frac{\Delta_U - \Delta_t}{\Delta_U} \quad (2)$$

Where: ac is the total area of stone columns group , A_{raft} is the total area of raft where in this study is 28 × 20, Δ_U is the settlement of untreated soil and Δ_t is the settlement of treated soil. Fig.12 shows the Replacement ratio “as” and improvement of soil settlement “is” at 100 kPa for different spacing. From the Fig.12, it can be seen that the optimum spacing from 2.15D to 2.5D with soil settlement from 173.85mm to 236.8mm. Soil settlements are improved from 58.91% to 44.03%.

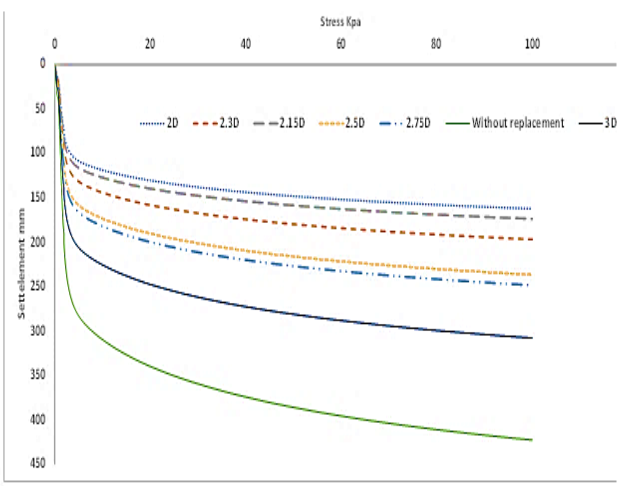


Fig. 11 Stress – settlement curves for different spacing.

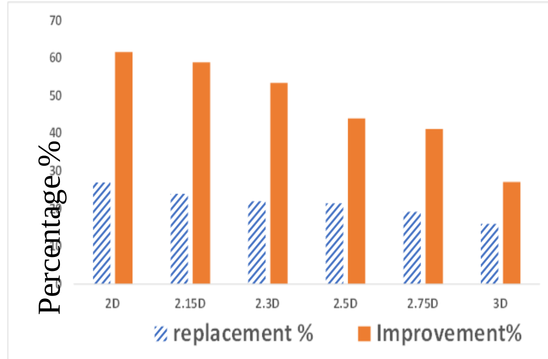


Fig. 12 Improvement %& Replacement % for different Spacing.

6.5. Effect of (t cushion /L) on Soil Settlement

The main function of the cushion layer is to distribute stresses before reaching the soft clay soil that surrounds the stone columns. Cushion thickness of values 0 m, 0.75 m, 1m (construction case), 1.25 m and 1.5 m are used. These thickness achives ratios ($t_{cushion}$ /L) of 0.125, 0.166, 0.2 and 0.25, respectively. The load settlement for different ratios of ($t_{cushion}$ /L) under raft load 100kPa are shown in Fig 13. From the Fig 13, it can be seen that the settlements are 228.65 mm, 195.35 mm, 190.2 mm (construction case), 174.434 mm, and 166.616 mm for ratios $t_{cushion}$ /L of 0.125, 0.166, 0.2 and 0.25, respectively. With increased cushion thickness to 1.25m and 1.5m, the soil settlement decreases by 8.28% and 12.4%, respectively compared with construction case. But when decreasing upper cushion thickness to 0.0m and 0.75m, the settlement increased by 20.22% and 2.71%, respectively compared with base case 1m upper cushion thickness. From an economic view, we recommend using the minimized thickness not less than a ratio of 0.125.

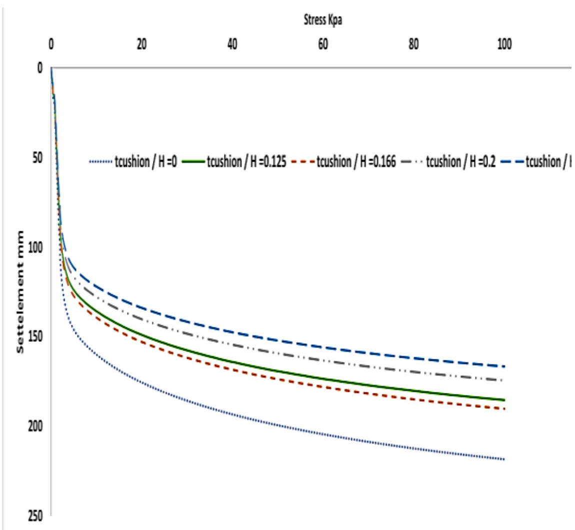
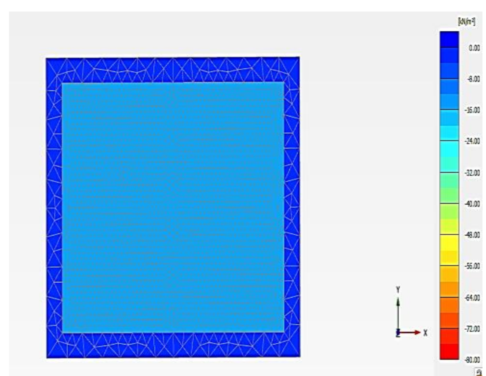


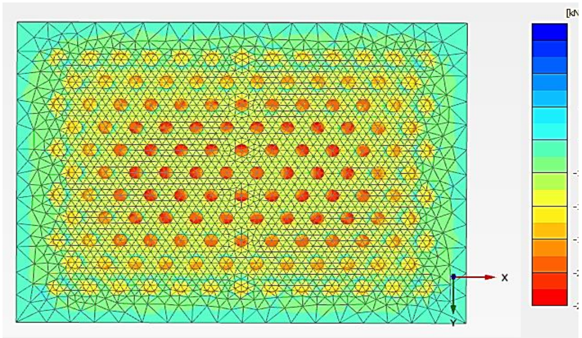
Fig. 13 Stress – settlement curves for different t cushion /L ratios

6.6. Effect of (Cc) on Concentration Ratio (n).

"n" is stress concentration ratio. Effect of different of (Cc) of lower lay layer was investigated for the improvement of soft clay soil. Figs.14 shows the stress on stones columns and surrounding soil at different loading phases for Cc =0.4. Different loading phases are after cushion and footing (before loading), at zero applied load (beginning loading) and at 100 kPa load (end loading). Figs.14 a & b & c show the stress at different loading phases before, beginning and end loading phases, respectively. As can be seen from Figs.14, concentration ratio increases in cushion and raft phase until beginning loading, then it decreases. Fig.15 shows the relationship between "n" and loading phases for different values of (Cc) of lower lay layer. As can be seen from Fig.15, (n) at the beginning of loading ranges for 16 at Cc = 0.4 and 10 at Cc = 0.8. With continuous loading (n) decreases to reaches 2 for all cases of (Cc). This can be interpreted as a result of loading transfer between soil and columns. That is, earlier, the column is taking about 16 times the stress in the soil at Cc = 0.4. With soil consolidation and columns deformation, the soil is carrying more loading. Such that, At the end of loading, soil takes 50% of the column loading. For Cc = 0.4, 0.5,0.6, and 0.7, under applied stresses of less than 20 kPa, the value of cc has a major effect on "n". While as, For Cc =0.8, under applied stresses of less than 35 kPa has a major effect on (n).



(a)



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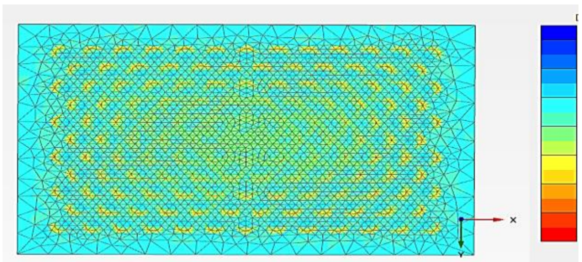

(c)

Fig. 14 Stress on stone columns and surrounding soil at different loading phases. a) before loading, b) beginning loading, and c) end loading

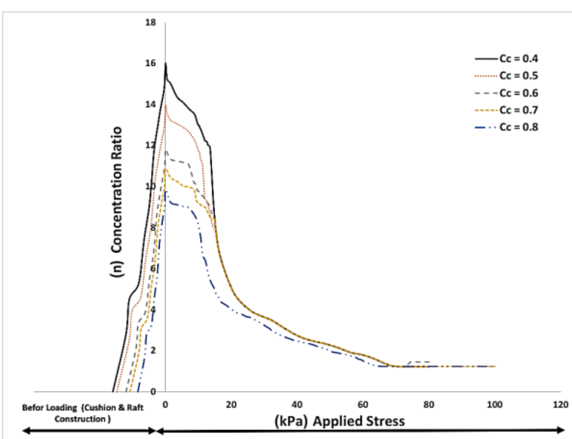

Fig. 15 The stress concentration ratio, n, during loading phases for different compression index

6.7. Effect of (Cc) on Settlement Under the Centreline of the Raft.

Settlement with time under the centerline of the raft was determined for different (Cc) of the layer clay layer. Fig.16 shows the relationship between the settlement and time. As can be seen from Fig.16, the settlement increases when the compression index increases. The settlements range between 173.26 mm to 525.13 mm for (Cc) 0.4 to 0.8. To avoid significant settlement, it is suggested to use a preloading technique soft clay layer when the lower clay layer compression index is greater than 0.4.

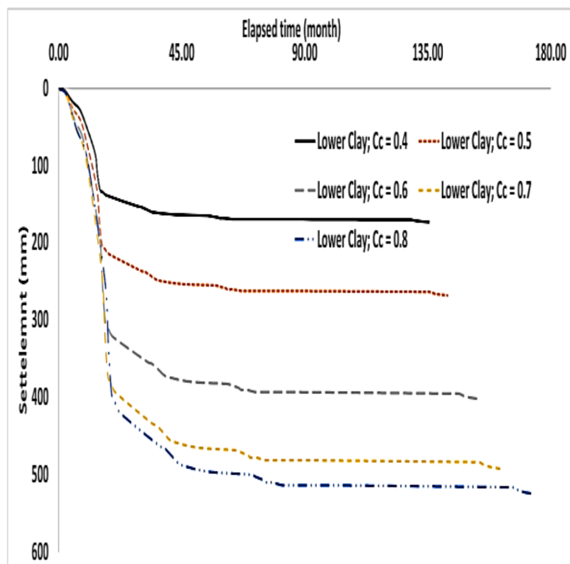

Fig. 16 Settlement and time for different Cc

7. CONCLUSION

Soft soil deposits have a weak bearing capacity and excessive settlement characteristics. It was suggested to stabilize soft soil with stone columns. Finite-element analyses have been performed for comprehensive numerical investigation on different parameters that affect the design of the suggested stone columns using PLAXIS 3D V.20 software. The effective parameters studied such as the ratio of the Length of stone columns to soft soil height L/H, the ratio of the diameter of stone columns to its length D/L, the distribution pattern, centroid spacing between stone columns, Cushion soil thickness, and Compression index of soft clay. Based on the numerical results, the following conclusions according to study case can be drawn:

1- The best ratio of L/H is from 1 to 1.25, which reduce the soil settlement from 48.91% to 58.91%.
2- The soil settlement is the same in equal replacement ratio alougth changing daimeter and spacing.
3- The best ratio of D/L is 0.166 which achieve the best reduction of settlement by 58.91%.
4- A triangular pattern distribution of stone columns is the best one because it gives the least soil settlement.
5- Optimum spacing between the centroid of stone columns of 2.15D-2.5D reduce the soil settlement by 24% to 21.4%.
6- The most depth of crushed stone cushion is 0.125 of the length of the stone column which has a significant effect on soil settlement and economic view.
7- It`s suggested using a preloading technique soft clay layer when the lower clay layer compression index is greater than 0.4.

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