Numerical Analysis of Ground Improvement by Group of Ordinary and Encased Stone Columns

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Abstract: The stone columns technique are widely used to improve the load settlement characteristics of soft soils either as an infinite pattern under wide spread loading or as a column group beneath shallow foundations. The design is usually based on analytical and semi-empirical procedures. For extreme raft, the analytical analysis is practically impossible due to the boundary modeling and the consumed time. This paper aims to develop 3-D numerical model to represent the soil and the stone column under the foundation. The numerical model is based on finite element (ABACUS- program). Comparative study is performed to determine the suitable analysis to evaluate the behavior of the stone columns group below foundation. The numerical results are calibrated with in situ-measurements.

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Key Words: stone column, soft clay, settlement, cam clay model, geosynthetics, geogrid, encased stone column, 3-D Numerical modeling, ABACUS.

1.Introduction:

Demand and restrictions on land suitable for construction has in recent times led to an increasing trend for the construction industry to exploit sites that were previously considered uneconomical to develop. The use of these sites for construction requires a coherent and economical construction technique to be applied. One of these sites is soft clay site particularly with great depth, where troubles during and after construction are expected due to its low shear strength and high compressibility. Sites of soft clay deposition are distributed along different places in Egypt at north coast, Delta, and Upper Egypt,) Osman *et al.,* 2001 (. Due to the development and economical growth in Egypt a lot of engineering and construction projects in these sites are most needed such as railways, roadways, and buildings.The stone columns technique of ground treatment showing a great success in increasing bearing capacity of soft soil, and reducing total settlements of soft soil, Malarvizhi, and Ilamparuthi (2007), Kirsch (2008) and Fattah and Khudhair (2010).

In General, stone columns are installed in group with regular grid. The columns may lie on the vertices of an equilateral triangle, a square or hexagon. Each stone column is assumed to be surrounded by an equivalent area of soil. This area can be closely approximated as a circle having the same total area and having an equivalent diameter (de) which represent the loading area, Goughnour and Bayuk (1979). The perimeter of each domain (unit cell) is shear free and undergoes no radial movement, Fattah and Khudhair (2010).

Most analytical design procedures deal with the improvement of the soft soils by an infinite pattern of stone columns or a single column. Both behave differently from a finite group of columns acting together to support single footing, Kirsh (2008). Therefore, numerical studies must carefully with in-situ measurements to determine the most probable numerical analysis fits with the in-situ measurements. The aim of this research is to examine the available methods of modeling infinite stone columns. A comparison between these models are performed and calibrated with the measured settlement of a case study.

2- Numerical Modeling

The problem of soft clay layer of 10.0m thick and rested on a bearing layer with a depth of 10.0m and reinforced with a group of infinite number of stone columns is considered. The unit cell concept as shown in Figure (1) is adopted to represent the behavior of the single stone column under loading. A comparative study has been carried out to model the behavior of raft foundation rested on soft to medium clay stabilized by group stone columns. The case of single footing 6.0 X 6.0 X 1.0m supported by group of stone columns (1, 5, 9 columns) is considered for comparison, Figure (2). The bottom boundary in all cases is restrained from movement vertically and horizontally while, the side boundaries are restrained from movement in the horizontal direction.

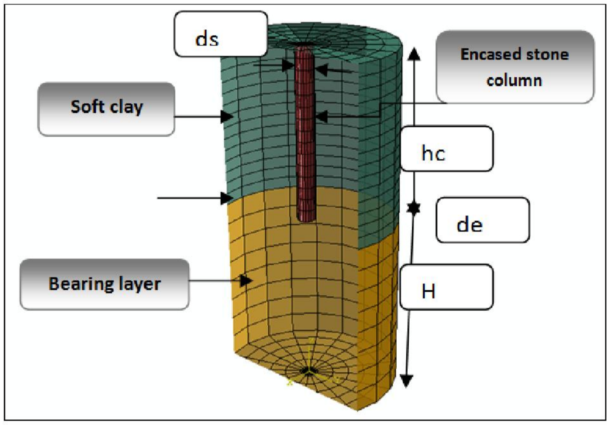


Figure (1): 3-D model of stone single column installed in soft clay, and rested on sand layer.

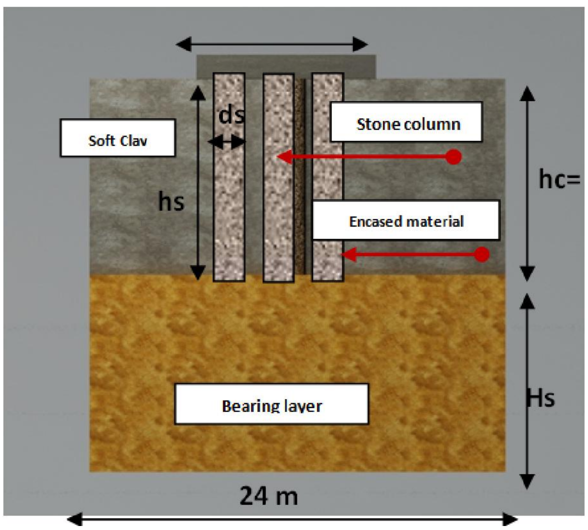


Figure (2) The Abaqus Finite Element Model

The non-linear behavior of the clay is represented by the modified cam clay model. The soft clay model is convenient to model normally consolidated clay. The soil parameters according to cam clay are given in Table 1, and they are adopted from Indraratna, *et al.* (2007). The values for λ and κ are obtained from one dimensional compression tests in oedometer, while the values of M were obtained from undrained triaxial tests with pore pressure measurements. The values of the earth pressure coefficients at rest, K_o, are related to (K_o = 1-sinφ). The stone column and the bearing layer are modeled using a linear elastic-perfectly plastic model with Mohr– Coulomb failure criterion. The soil parameters of the granular soil used in the numerical analysis are quoted after Khabbazian *et al.* (2010). The encased geosynthetic material was modeled as an isotropic linear elastic material with a tensile stiffness (J) of 3000 kN/m (El Kaisouny 2013) and a Poisson's ratio of 0.3. The circumferential elastic modulus (E) of the geosynthetic was derived from the relationship J = Et, where t is the thickness of geosynthetic, which was assumed to be 5 mm for all of the numerical analyses performed. (Khabbazian *et al.*, 2009).

The Interface elements were used to model the interaction behavior between the stone and the encased material and between the encased material and soft clay. The interface friction angle was assumed to be equal to the friction angle of the stone, (Liu *et al.*, 2007). The coefficient of sliding friction (μ) between the geosynthetic and the stone column was selected to be 0.5 (μ=2/3tanφ) (FHWA, 2006), where φ is the friction angle of the column material. For interaction between the geosynthetic and the soft soil, μ was assumed to be 0.3 (μ=0.7tanφ) (Abu-Farsakhl *et al.*, 2007), where φ is the friction angle of the soft soil, (Khabbazian *et al.*, 2010).

Table 1: Soil Parameters of FEM analysis

Property	Symbol	Stone column (Mohr-coulomb)**	Material	
			Soft soil * (MCC)	Bearing layer (Mohr-coulomb)
Sat. unit weight **kN/m^3**	**γ**	**20**	**16**	**18**
Young's modulus **kPa**	**E**	**60000**		**60000**
Poisson's ratio	**ν**	**0.3**	**0.25**	**0.3**
Friction angle deg	**φ**	**40**		**30**
Dilatancy angle	**ψ**	**10**		**10**
Critical state stress ratio,	**M**		**1.2**	
logarithmic hardening constant for plasticity	**λ**		**0.5**	
Logarithmic bulk modulus for elastic material behavior	**κ**		**0.05**	
Initial void ratio	**e_o**	**0.4**	**2.4**	**0.5**
Permeability **m/s**	**k_v**	**1e-4**	**6e-10**	**1e-2**

*Indraratna *et al.* (2007)
**(Khabbazian *et al.* (2010)

The clay layer is modeled by twenty node stress-pore pressure coupled brick elements with reduced integration (designated C3D8RP, while the stone column and the bearing layer, while 20 node brick geosynthetic was modeled using 4-node quadrilateral, reduced integration membrane elements (M3D4R).

The proposed Abaqus finite element model, using the unit cell concept, is calibrated with the well document experimental and numerical results published by Malarvizhi, and Ilamparuthi (2007). The experimental test was carried out on a single ESC of diameter 30mm for variable Ls/ds ratio (Ls= length of the column; ds= diameter of the column). The size of the tank was 300mm in diameter and 300mm in height. The equivalent diameter of the tributary area for a spacing of 2ds in square pattern is 2.3ds which represent the loading area. The published results, both experimentally and numerically, are shown in Figure (3) as well as the deduced results obtained in this study for different Ls/ds ratio. Thus the proposed model is considered adequate to represent the problem of ESC embedded in soft clay.

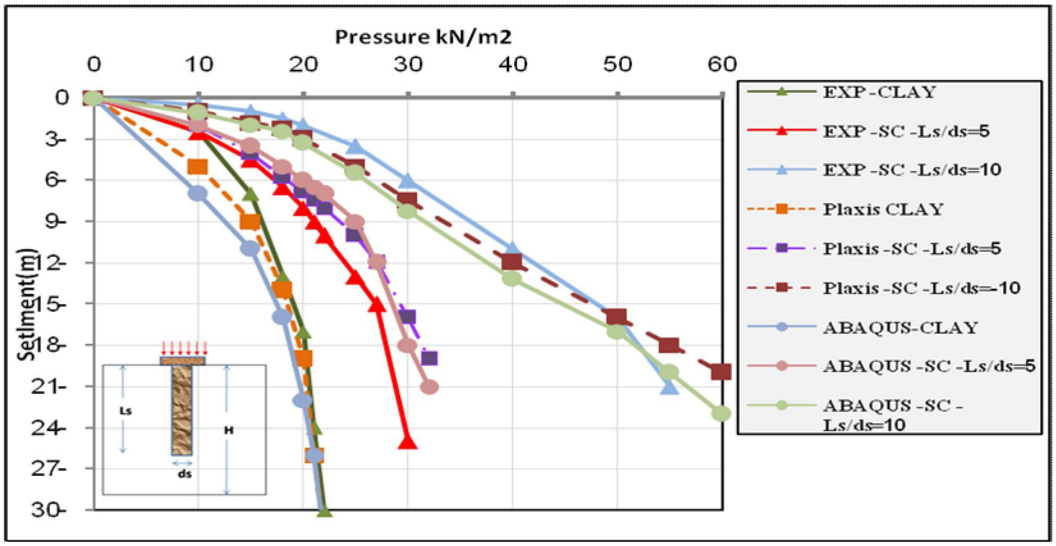


Figure (3) Comparison between Load vs settlement curves resulted from Abaqus Model and those obtained by Malarvizhi and Ilampraruthi (2007) for different Ls/ds ratio

3- Results

In general, there are four cases of loading the stone columns:

i. Loading the stone column only (this is out of the scope of this study).

ii. Loading the entire surface area of the unit cell with an external diameter twice the stone column. This case represents the behavior of group of infinite number of stone columns.

iii. Loading the stone column and a circular area of the soil surrounding the column of diameter of loading 3ds, considering the diameter of the outside boundary is 10ds. (this is a trail to simulate the actual boundary of the central column on a group where radial movement may be occurred).

iv. Loading a single square footing supported by number of stone column.

The results for the different case of loading are represented and discussed in the following.

3.1 unit cell

In the unit cell the load is applied incrementally on the columns through a rigid steel circular plate with diameter equal to twice the column diameter,2ds, and with a thickness of 100mm. The encased stone column (ESC) is fully encased with geosynthetic material with high tensile strength (J=3000 kN/m). The stress settlement curves for ordinary stone column (OSC) and encased stone column (ESC) loading according to case (ii) are shown in Figure (4). To avoid the effect of the boundary conditions on the results, the diameter of the unit cell is chosen to be 10ds (El Kaissouny 2014), while the loading area is kept constant with diameter 2ds, loading case (iii). The load is applied on the column through the loading plate (2ds in diameter).

No difference in the behavior of OSC and ESC is detected during loading the entire cell, case (ii), irrespective to its diameter. This is due to the confinement of the cell as a result of the assumption. This confinement masked the effect of the encasement of the column. The lateral bulging of the ESC and OSC as shown in Figure (5) confirms this observation. However, partially loaded cell case (iii) proves that casing the stone column resulted in a decrease in the settlement with respect to OSC. Comparing the results obtained from case of loading (ii) and (iii), it can be concluded that for ESC the resulted settlement due to loading case (ii) is approximately 1/3 of that obtained from loading case (iii). For OSC the resulted settlement from loading case (ii) is about 1/5 that obtained from loading case (iii). This means that the unit cell concept representing the central column in a group yields different results depending on the assumed boundary condition.

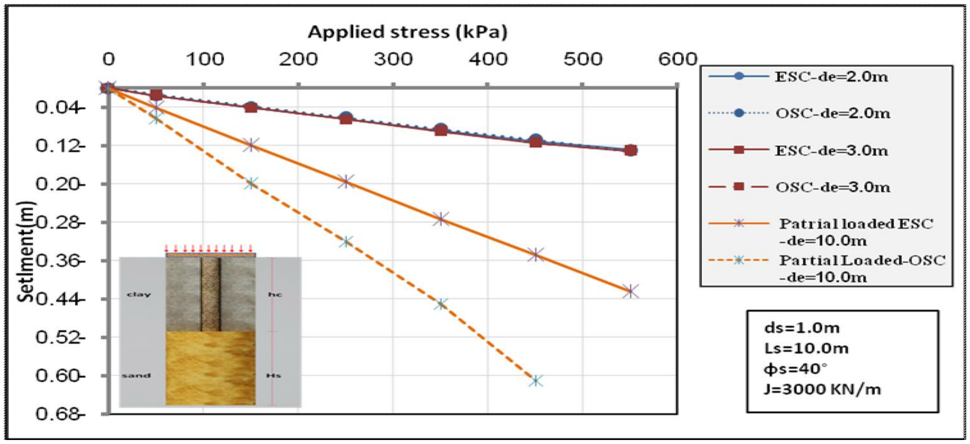


Figure (4) Stress – settlement curve for different unit cell diameters

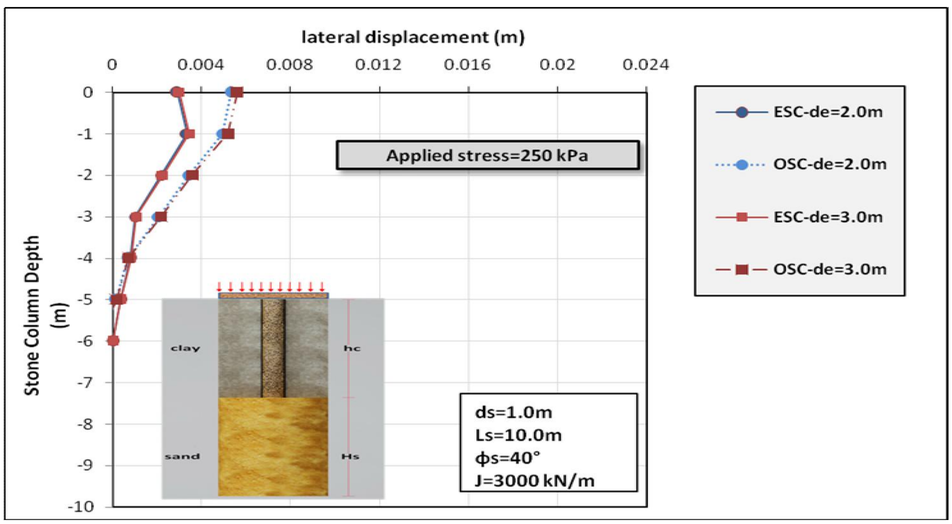


Figure (5) The lateral bulging profile of OSC and ESC for different unit cell diameters

3.2 Single Footing

Generally OSC and/or ESC installed in soft clay bed are used to support single footing in order to minimize the post construction settlement. The overall objective of these study focuses on investigating the bearing behavior of loading reinforced footing rested on soft clay using 3D FE analysis considering the ESC interface model. A single footing with dimension of 6.0X6.0 m and 1.0m thick is supported with different number of stone columns, ESC /OSC, (1,5 and 9) with diameter (ds) 1.0m imbedded in soft clay with a length (hc) of 10.0m which is the depth of soft clay. The spacing between the columns is kept constant and equal 2ds.. The bearing layer is sand with depth of 10.0m. The boundary of the model extended to 24.0m in X and Y direction. Soft soil was modeled as modified cam clay materials. The soil properties and the granular material are given in Table (1). The encased geosynthetic material was modeled as an isotropic linear elastic material with a tensile stiffness (J) of 3000 kN/m (Eg=600Mpa) and a Poisson's ratio of 0.3.

The stress- settlement curves of the footing rested on the composite soil reinforced by a group of OSC and ESC are shown in Figure (6). It is noticed that as the number of the stone columns supported the footing increases (i.e the area ratio As/A), where As = cross-sectional area of one column and A = total cross-sectional area of the loading area), the resulted settlement decreases for both OSC and ESC. The area ratio of about 0.2 (which represent nine column under the 6.0X6.0m footing), represents the most practical ratio used in the design (Kirsch (2008), Zahmatkesh and Choobbasti (2010)). Thus the stress-settlement curves for OSC and ESC with an area ratio of about 0.2 is used in the comparative analysis. Increasing the area ratio from 0.04 (one stone column) to 0.2 (nine stone columns) increases the capacity by 1.6 and 1.3 for ESC and OSC respectively. Consequently, it can be concluded that, as the number of stone column increases the global modulus of deformation increases.

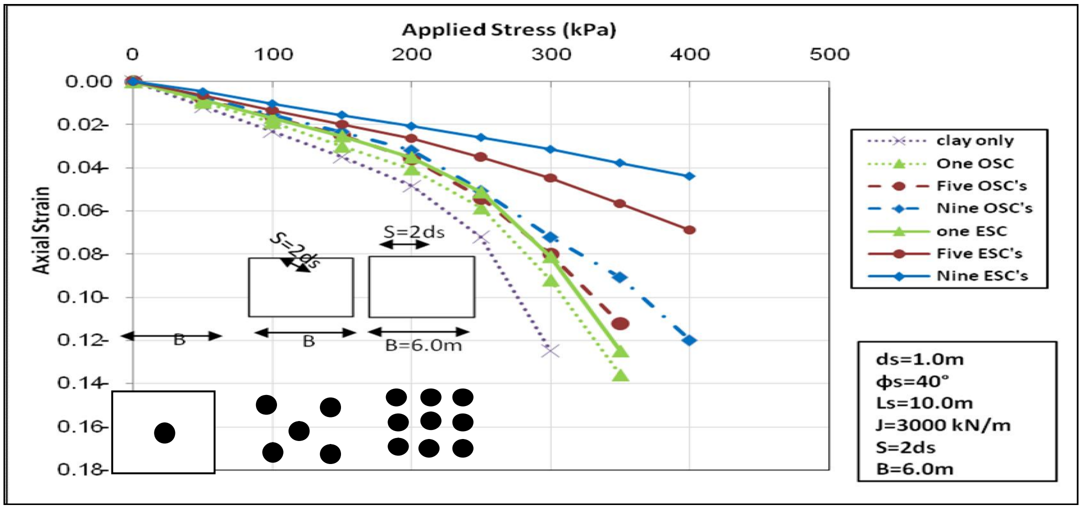


Figure (6) Stress-strain curve for raft supported with different number of stone columns

3.3 Comparative Analysis

The stress-settlement curves for OSC and ESC with an area ratio of about 0.2 are compared with the resulted stress-settlement relation obtained from different loading cases (ii,iii). Figures (7) and (8) represent this comparison for OSC and ESC. The shape of stress –settlement curves obtained using loading cases (iii, iv) are similar but they are different than obtained when using loading case (ii).

The settlement at applied stress of 100 kPa and 200 kPa obtained from the different case of loading case of (ii,iii,iv) for OSC and ESC are given in Tables 2,3.

Table 2 Settlement at 100 kPa and 200 kPa for OSC

Stress level	Settlement		
	Central column in grouping (9 cols) (M1)	Partial loaded (de=10) (M3)	Total loaded (2ds) (M2)
at 100 kPa	0.154	0.13	0.068
at 200 kPa	0.35	0.28	0.115

Table 3 Settlement at 100 kPa and 200 kPa for ESC

Stress level	Settlement		
	Central column in grouping (9 cols) (M1)	Partial loaded (de=10) (M3)	Total loaded (2ds) (M2)
at 100 kPa	0.1	0.09	0.06
at 200 kPa	0.21	0.18	0.1

Figure (7) and (8) represent the settlement applied stress curves for totally and partially loaded unit cell (model M3 and M2 respectively) as well as that of reinforced footing with dimension (6x6x1m), supported by nine encased stone columns (model M1). The results indicate that, the stone columns group (M1) yields settlement of about 1.2 that obtained due to loading (iii) under any stress level for OSC and ESC. Comparing the results of the single footing with the confined unit cell, case (ii), the settlement of the footing supported by OSC is about 1.75 that of obtained from loading case (ii) at 100kPa and 2.75 at 200kPa. These values become 1.6 and 2.0 for ESC at applied stress 100 and 200 kPa respectively. It is noted that the encasement of the stone column has a negligible effect on the resulted settlement, loading case (ii).

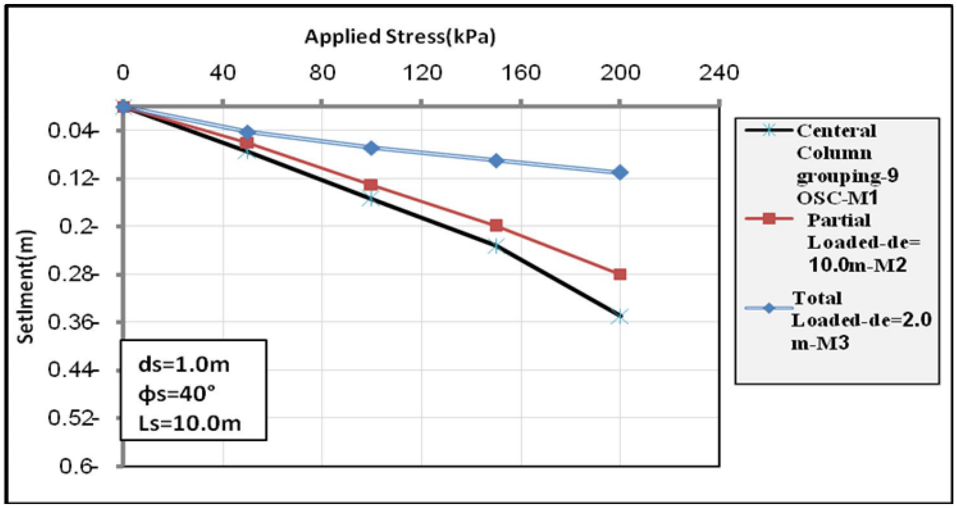


Figure (7) Stress–settlement curve for investigated models M(1), M(2) and M(3) using ordinary stone column

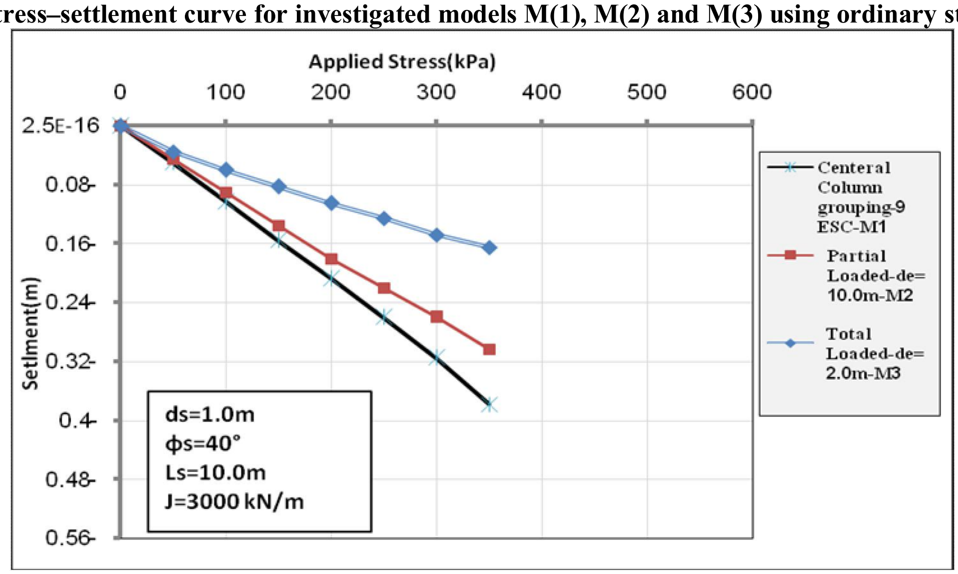


Figure (8) Stress–settlement curve for investigated models M(1), M(2) and M(3) using encased stone column

4 Case Study

To investigate the effect of stone column technique in increasing the strength of the soft soil and decreasing settlement, a full scale structure in Wadi El Nile Street at Giza city was built over soft clay reinforced with ordinary stone columns. The full scale structure building was built over land of 20 X 16 m. The building was planned to have one basement and twelve floorings. The structure building was constructed over raft foundation with depth 1.10m supported over 236 stone columns of diameter 0.4m and spacing 1.2m and 5.0m depth. The foundation soil is medium clay with 5.0m depth rested over sand layer of 7m depth. Standard tests were performed to determine the physical and mechanical properties of the soil and Figure (9) shows the soil stratification and properties. Field observations of the settlement were carried out using total station device by marking signs at some reinforced columns (six remarks) at the ground floor, Figure (10). The settlement was recorded during the construction period for about 15 months. Figure (11) shows the average settlement against the average applied stresses for the six points.

The proposed numerical model of the unit cell, totally loaded and partially loaded, is calibrated by the measured settlement of the reinforced footing. The outside diameter of the unit cell in case of the totally loaded is 3ds while in case of partially loaded the outside diameter is taken 10ds. The loaded area is kept constant in both cases with diameter of 3ds. The stone column is 0.40m in diameter and 5.0m depth. The clay is modeled as modified cam clay material and the stone column and the bearing layer are modeled using a linear elastic-plastic model with Mohr-coulomb criterion and Table 4 represents the used soil properties.

Table 4 Parameters used in the analysis

Property	Symbol	Stone column (Mohr-coulomb)	Material	
			Soft soil (MCC)	Bearying layer (Mohr-coulomb)
Sat. unit weight **kN/m^3**	γ	20	16.8	18
Young's modulus **kPa**	E	80000		60000
Poisson's ratio	ν	0.3	0.25	0.3
Friction angle deg	φ	40		35
dilatancy angle	ψ	10		10
Critical state stress ratio	M		1.4	
logarithmic hardening constant for plasticity	λ		0.3	
Logarithmic bulk modulus for elastic material behavior	κ		0.03	
Initial void ratio	e_o	0.4	1.6	0.5
Permeability **m/s**	k_v	1e-4	2.5e-9	1e-2

A comparison between the measured average axial strain - average stress and those deduced from the numerical analysis using the unit cell concept, Figure (11). Curve B2 represents this relation in case of partially loaded cell while curve B3 represents the relation in case of totally loaded unit cell. It can be concluded that the field measurement is greater than that produced from the analytical analysis. The field axial strain at applied stress of 150kPa is about 1.15 times that in case of partially loaded cell. At the same applied stress the field measurement is about 1.5 times that of the totally loaded cell. The secant tangent modulus at applied stress 150 kPa are 27.5, 39.5 and 53.0 Mpa for measured, partially and totally loaded cell respectively. This finding is consistent with that obtained in section 3-2 (Figure (7)) which indicates that the settlement of group of stone column is approximately 1.2 times that of obtained from partially loaded cell. For ordinary stone columns and at high applied stress 210 kPa, the group of columns yields settlement which is more than twice that of totally loaded unit cell.

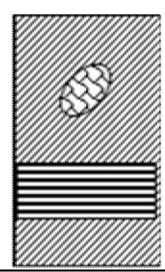
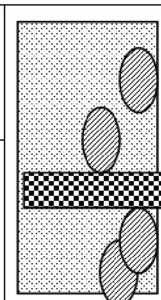
The soil specification	g bulk Kg/cm3	S200 %	NN	$q_{u(Kg/cm2)}$	specification	Depth (m)
Silty clay (Dark brown) ▪ LL=70% ▪ PL=28% ▪ Wc=39%	1.78			1		1
				1.1		2
				1.1		3
				1.2		4
				1.2		5
						6
				1.1		7
				1.2		8
				1.1		9
Medium to coarse sand	1.6	6	35			10
						11
						12
		2	47			13
						14
						15

Figure (9) The physical and mechanical properties of the soil

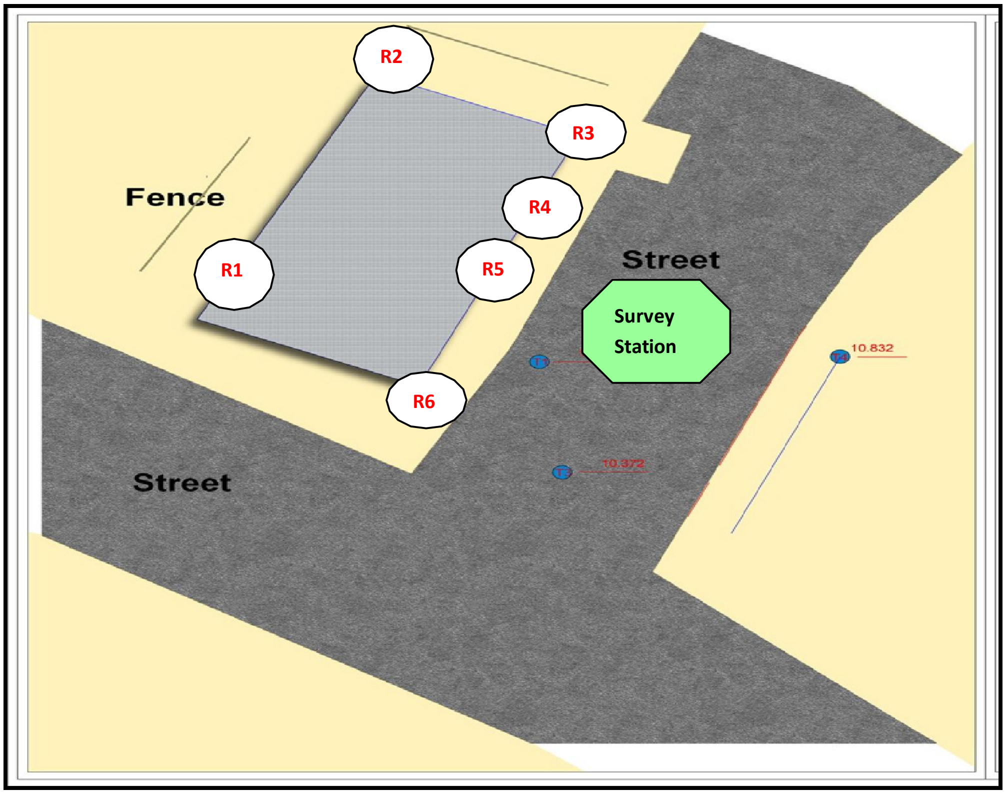


Figure (10) The remarked sign at each reinforced columns at the ground floor

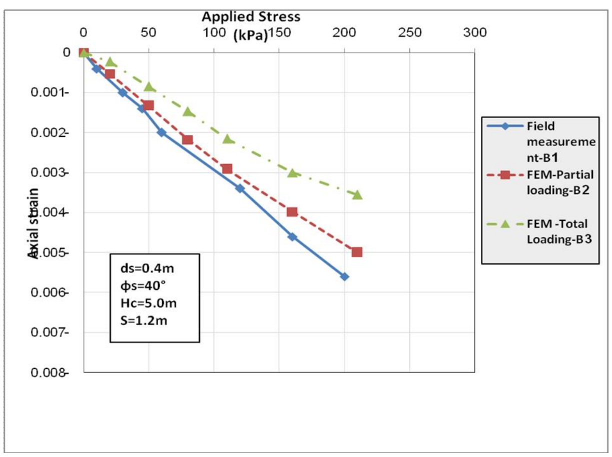


Figure (11) Comparison between the predicted stress –strain curves and the measured one for the case study

5-Conclusion

Based on the numerical work carried out in this research as well as the case study, the following conclusions can be drawn:

1. The numerical model used in the analysis is calibrated with published experimental results and prove to be valuable for predicting the deformation.
2. Representing the infinite number of stone columns by unit cell with outside diameter equal the spacing of the columns, totally loaded, yields to stress-settlement curve similar to that obtained from oedometer test. This case under estimate the settlement under any stress due to the confinement assumed at the boundary.
3. This case of loading, unit cell with outside diameters(2ds), and totally loaded masked the effect of casing the stone column i.e. the stress-settlement curves for both OSC and ESC are the same.
4. Partially loaded unit cell with outside diameter of 10ds and loaded partially produces greater settlement than the totally loaded cell. This case of loading shows that the encased stone column settles less than ordinary one.
5. Footing supported by a group of columns, the resulted settlement decreases as the number of the columns increases. This is due to the increase of the global modulus of deformation of the composite matrix.
6. Comparing the applied stress- settlement curve of footing supported by group odf stone columns (with area ratio of 0.2) with those obtained using unit cell with variable loading conditions, revels that:
   a. The footing settlement is 1.2 that obtained in case of partially loaded unit cell for both OSC and ESC as the boundary effect is negligible.

b. The settlement of totally loaded cell is less than half of the settlement of footing supported by group of stone columns (OSC and ESC).

7. The measured settlement of case study of a raft supported by 236 ordinary stone columns is compared with those obtained using the numerical analysis for the unit cell at applied stress of 150 kPa is 1.15 times that obtained using partially loaded cell and about 1.5 times that totally loaded. This indicates that using partially loaded is convenient.

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