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Research Article

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Numerical Investigation of Encased Stone Columns in Soft Clay Soils

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Abstract Soft soil deposits are prevalent in various regions of Egypt, including Eastern Port Said, Suez Canal, Damietta, Kafr El-Sheik, and Alexandria. The development that extends in those regions have confronted the test of the nearness of extended deep layers of soft clays. Stone columns are usually used to help structures overlying soft ground soils and surcharged by embankment type loading. Therefore, this paper is simply represent a wide numerical comparison study between Encased Stone Column (ESC) (L/H=1), ESC (L/H=0.7), and ESC (L/H=0.5) installed in soft clay soil using finite element method (FEM), and (Proposed Analytical Solution), to determination the improvement factor. Parametric study of an embankment on soft soils reinforced with stone columns is performed using a commercial computer program (Plaxis 2D) based on the (FEM). The investigation presented the influence of the following parameters: diameter of stone columns on the required consolidation time, Length of stone columns, and settlement of soft clay. Results indicated that using ESC (L/H=1.0) is better than using ESC (L/H=0.7), and ESC (L/H=0.5). The results obtained from the (FEM) were in good agreement with the proposed analytical solution. The settlement behavior of clay was improved based on the ratio of diameter ratio(R). Thus, by decreasing the ratio of R, with consideration of the end bearing stone column, the settlement of the soft clay was decreased.

Keywords Stone Column, Soft Clay, Consolidation, Finite Element Analysis

1. Introduction

Structures built on soft strata may experience problems such as excessive settlement, large lateral deformation of instability. Ground improvement with an emphasis on the stone column technique overcomes these problems by reducing the total settlement under loading and speeding up the consolidation process. The existence of the columns creates a composite material, stiffer than the original soil, which attains its load capacity from the confinement provided by the surrounding soil. When stone columns are installed in extremely soft clay, insufficient lateral confinement, especially in the upper portion of the columns, may significantly reduce their capacity.

Stone columns have been used extensively over the last three decades in numerous ground improvements, and foundation projects [1-4]. Stone columns provide the primary functions of reinforcement and drainage by improving the strength and deformation properties of the soft soil. Stone columns increase the unit weight of soil (due to densification of surrounding soil during construction), dissipate quickly the excess pore pressures generated and act as strong and stiff elements and carry higher shear stresses [5]. Applications of stone columns include support to embankments, liquid storage tanks, raft foundations and other low-rise structures. The passive resistance of the surrounding soil dictates the column performance under load. Generally, the column bulging will be greatest close to the top of the column where the overburden pressures are lowest. Priebe [6] proposed a method to estimate the settlement of foundations resting on an infinite grid of stone columns based on the unit cell concept. In this concept, for an infinitely large group of columns subjected to a uniform vertical loading applied over the area, the behavior of each interior column may be simplified to a single column installed at the center of a cylinder of soil representing the column's influence zone. Due to the symmetry of the load and geometry, lateral deformation cannot occur across the boundaries of the unit cell, and the shear stresses on the outside boundaries of the unit cell must be zero.

Ambily and Gandhi (2007) [7] carried out a detailed experimental study on behavior of single column and group of seven columns by varying parameters like spacing between the columns, shear strength of soft clay and loading condition. Murugesan and Rajagopal (2006) [8] performed axis symmetric finite element analyses to examine the behavior of OSC, and ESC. They reported that the depth of encasement equal to two times the diameter of stone column is adequate to substantially increase its load carrying capacity. Yoo (2010) [9] numerically investigated the performance of ESC installed in soft ground for embankment construction. He reported that full encasement may be necessary to ensure maximum settlement reduction when implementing ESC under an embankment loading condition. Fattah et al. (2012) [10] were investigate on FEM of Stone Columns. They show that the bearing improvement ratio and the settlement reduction ratio are increased with decrease in undrained shear strength of the surrounding soil for all end bearing soil undrained shear strengths. This paper presents a wide numerical comparison study between ESC (L/H=1), OSC (L/H=0.7), and OSC (L/H=0.5) installed in soft clay soil using (FEM), and (Proposed Analytical Solution), to determine the improvement factor.

2. Numerical Analysis Verification

The analysis was carried out using an available package Plaxis 2D, to compare the load settlement behavior with the model test. The package was validated by analyzing the load settlement behavior of a single stone column by Surat (2012) [11]. The tank model he use has a height of 450mm, and diameter of 260 mm of soft clay soil, and with a single stone column of 50 mm diameter. Properties of clay and stones are shown in Table 1. An axisymmetric analysis was carried out using Mohr-Coulomb's criterion for clay and stones. The results obtained from the Plaxis 2D models are in good agreement with the experimental results, as shown in Figure1.

Table 1: The soil properties which used by Surat (2012) [11].

Material	E (kPa)	C (kPa)	φ	Ψ	ν
Very soft clay	2550	9	0	0	0.35
Granular column	21000	0	30	4	0.30

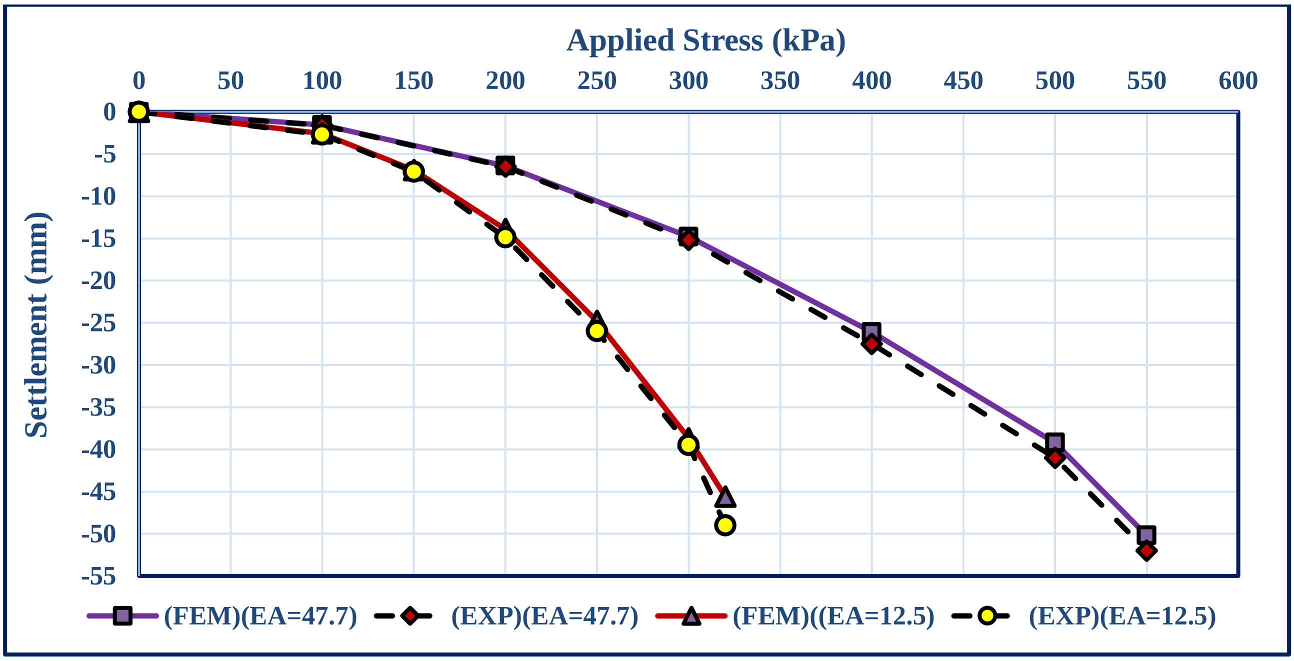


Figure 1: Verification of FEM with Surat (2012) [11]

3. Analysis of Stone Columns

Plaxis2D, finite element analysis was carried out for soft clay and for the same clay modified by single stone column under static load for a sufficient period of time to ensure full consolidation is attained. To determine this period, a sensitivity analysis was carried out, as shown in Figure 2. It was found that 560 days is considered a reasonable period to be used in the model. For consolidation analysis, coupled consolidation concept was supposed. The different diameters of the stone column were applied for the analysis, and the results were compared. The axisymmetric unit cell was analyzed. During consolidation analysis, the loading applied was assumed to be uniform, and it was assumed that it was applied immediately through the clay layer. During the consolidation analysis, the distributed load was assumed to remain constant. The stone column behaves like drain wells within the unit cell. The results of finite element analysis for treated clay by stone column, and untreated soft clay were compared. The model's geometry are illustrated in Figure 3. Properties of soft clay soil and stone column material, beside the geogrid material, are given in Table 2.

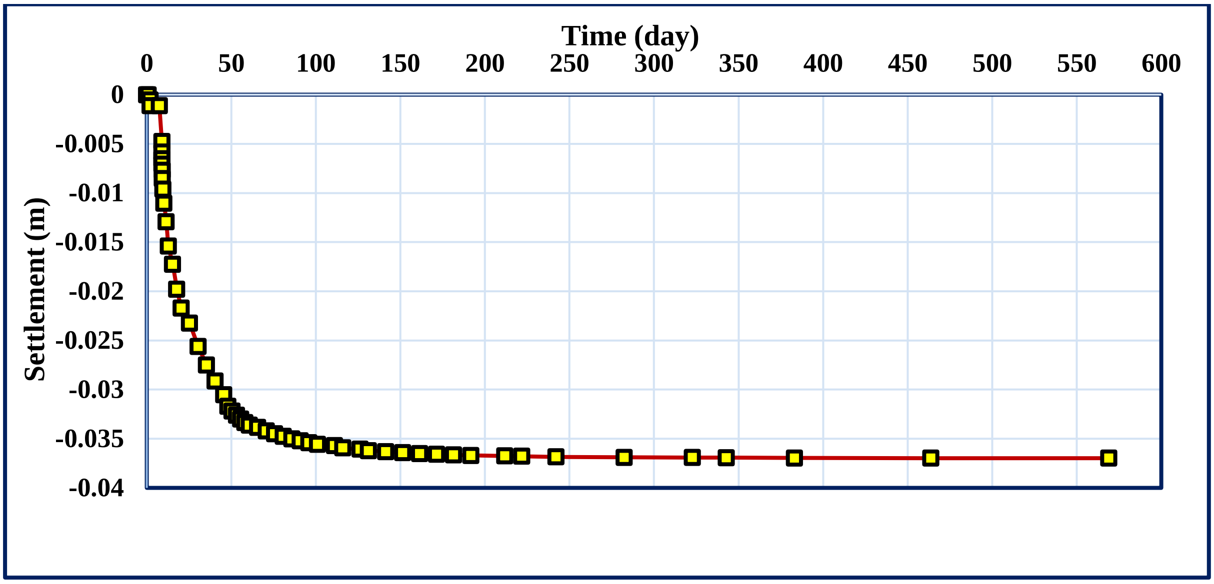
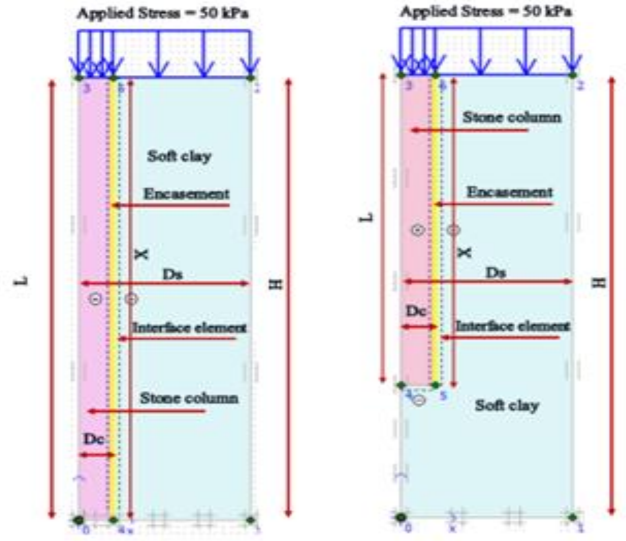


Figure 2: The maximum displacement after 560 days



(a) *(b)*

Figure 3: (a) Unit cell end bearing total ESC, and (b) Unit cell floating ESC

Table 2: The properties of soft clay, stone column, and geogrid used in models.

Material	E (kPa)	C (kPa)	φ	Ψ	ν	EA (kN/m)
Soft clay	2700	15	0	0	0.33	-
Cursed stone	30000	0	42	12	0.30	-
Geogrid	-	-	-	-	-	3000

4. Proposed Analytical Solution

Current analytical methods for calculating settlement can be classified as either (1) simple, approximate methods which make important simplifying assumptions or (2) sophisticated methods based on fundamental elasticity and/or plasticity theory (such as FEM) which model material and boundary conditions. All of these approaches for estimating settlement suppose an infinitely wide, loaded area reinforced with a stone column having a constant diameter and spacing. For this condition of loading and geometry, the extended unit cell concept is theoretically valid. Several analytical methods are introduced to estimate settlement of soil treated with stone columns. Most of these methods deal only with ordinary stone columns. In the following sections, an analytical solution to estimate settlement of end-bearing ESC, and floating ESC is introduced. It worth noting that the proposed analytical solution is applicable for the used soil properties.

End bearing geogrid encased stone columns

The main advantage of the proposed analytical solution that it offers simple engineering approach for estimating settlement of improved soil reinforced by end bearing ESC, as shown in Figure 4.

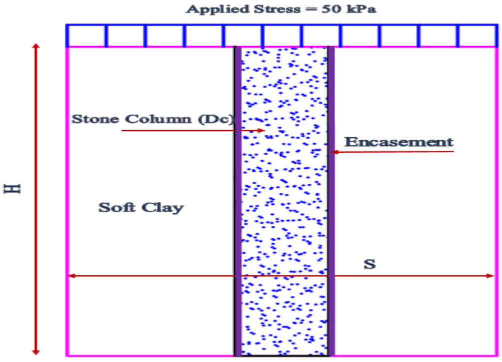


Figure 4: Main symbols used for proposed analytical solution of End bearing ESC

The proposed analytical solution is given in the following equations:

$$\text{Settlement} = \frac{Q*H}{E_{eq}\,\text{csg}} \tag{1}$$

$$E_{eq}\,\text{csg} = \frac{E_s}{(1-\nu_s)} * (1\text{-}As) + \frac{E_c}{(1-\nu_c)} * (As) + \frac{EA}{\text{Column Perimeter}} \tag{2}$$

Floating geogrid encased stone columns.

The main advantage of the proposed analytical solution that it offers simple engineering approach for estimating settlement of improved soil reinforced by floating ESC, as illustrated in Figure 5.

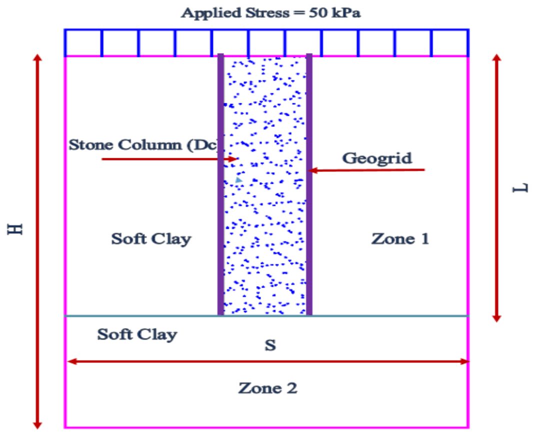


Figure 5: Main symbols used for proposed analytical solution of floating ESC

$$\text{Settlement (zone 1)} = \frac{Q*L}{E_{eq}\ csg} \tag{3}$$

$$\text{Settlement (zone 2)} = \frac{Q*(H-L)}{E_{eq}\ s} \tag{4}$$

$$\text{Settlement Total} = \text{Settlement (zone1)} + \text{Settlement (zone 2)} \tag{5}$$

$$E_{eq}\ csg = \frac{E_s}{(1-\nu_s)} * (1\text{-}As) + \frac{E_c}{(1-\nu_c)} * (As) + \frac{EA}{\text{Column Perimeter}} \tag{6}$$

5. Discussion

To obtain the effective column length (based on L/H ratio), Twelve FEM models were performed on soft clay soils reinforced with geogrid encased stone column with four different ratios of (R =7.5, 5.0, 3.75, 3.0). Different L/H ratios (L/H = 1.0, 0.70, 0.50) were used. The main aim of those models is to choose the effective L/H ratio of floating ESC compared to end bearing ESC (L/H = 1.0).

Figures 6 to 11 showed that increasing the ratio of column length to the clay deposit thickness leads to a significant improvement in the settlement. As the length of the ESC increased, the ultimate load carrying capacity increased, and the settlement decreased. The ultimate load carrying capacity increased, and the settlement decreased for end bearing ESC than for floating ESC with different L/H ratios for all R ratios used as illustrated in figures 6, and 7.

Based on the model results, the settlement curves of the soft clay soil in case of end bearing ESC with (R =7.5, 5.0, 3.75, 3.0) is decreased by ratio 10%, 30%, 48%, and 68%, respectively compared to the settlement curves of the soft clay soil in case of floating ESC (L/H=0.70). While is decreased by ratio 30%, 40%, 61%, and 88%, respectively compared to the settlement curves of the soft clay soil in case of floating ESC (L/H=0.50), as illustrated in Figure 8.

The proposed analytical solution for end bearing ESC was compared against results of the finite element model and good agreement was found, as illustrated in figures 9,10, and 11.

The results of the analysis indicated that the performance of geogrid encased stone column of smaller diameters is superior to that of larger diameter stone columns for the same encasement especially at R=5.0 because of mobilization of higher confining stresses in smaller diameter stone columns. The higher confining stresses in the column leads to higher stiffness of smaller diameter geogrid encased columns.

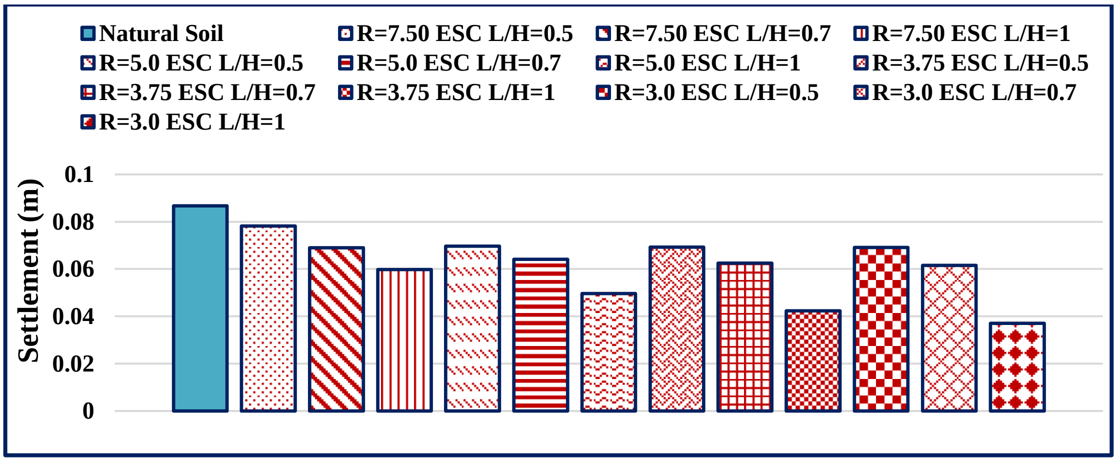


Figure 6: The maximum displacement after 560 days in case of end bearing, and floating ESC

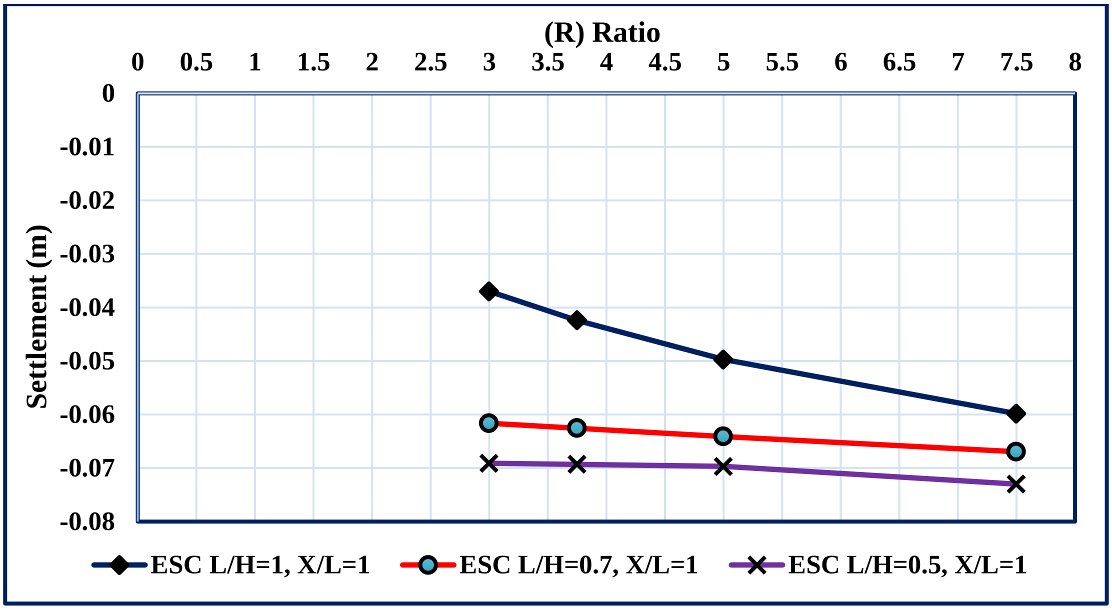


Figure 7: Effect of column length (L/H) ratio in case of ESC

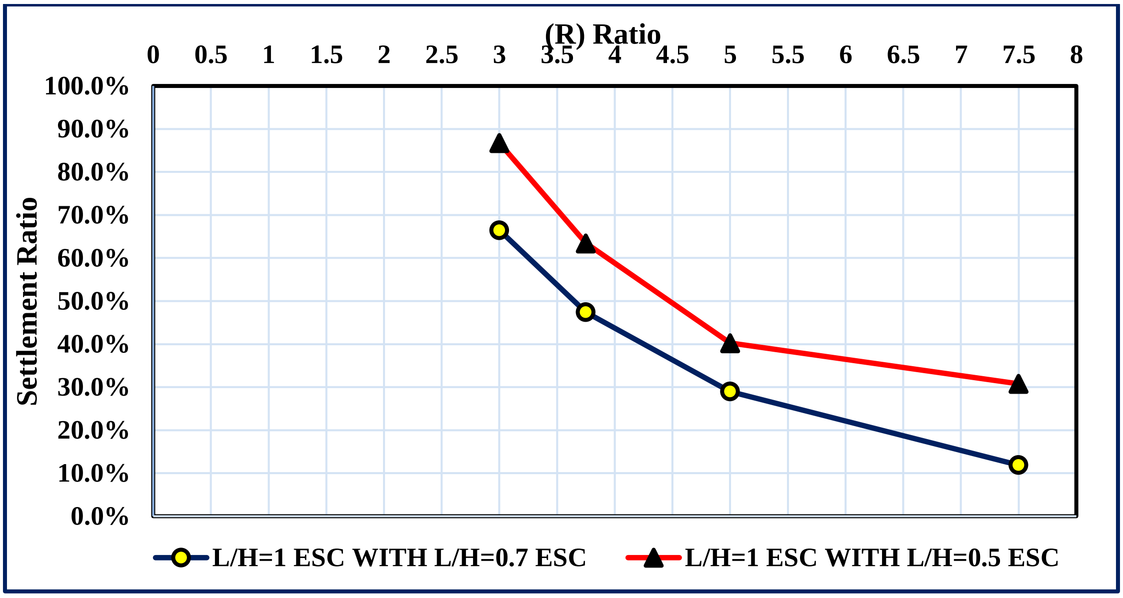


Figure 8: Improvement ratio of using full column versus partial column length

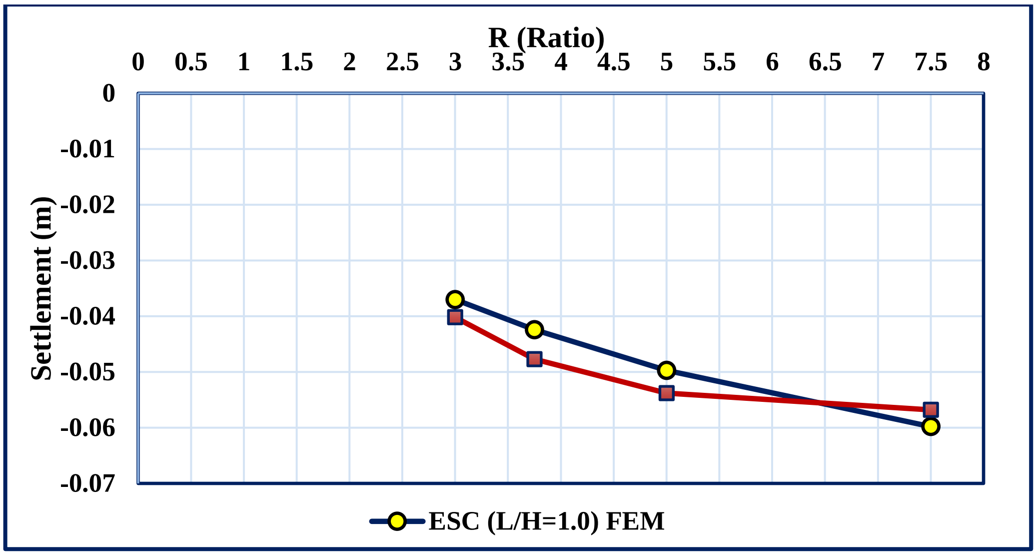


Figure 9: Comparison between FEM and analytical solution results in case of end bearing ESC (L/H=1.0)

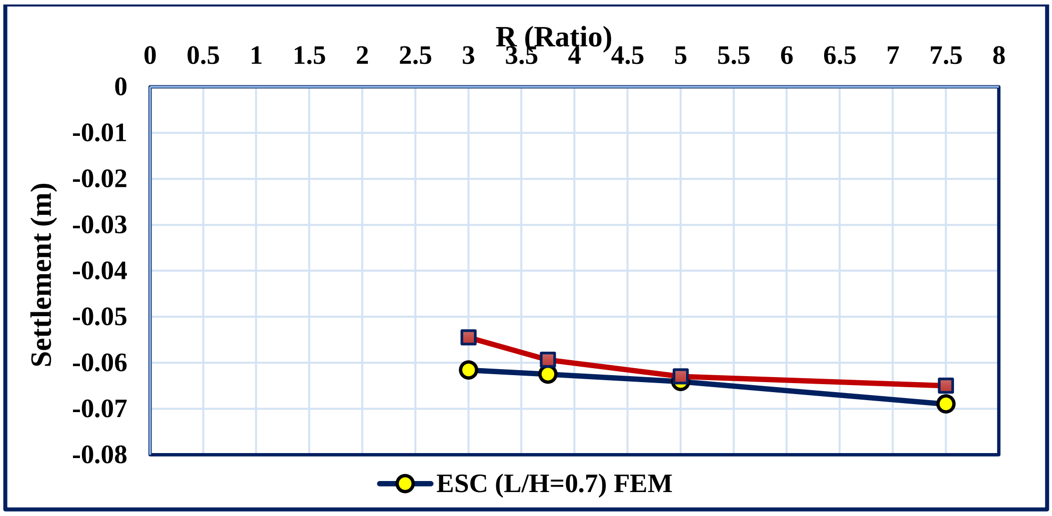


Figure 10: Comparison between FEM and analytical solution results in case of floating ESC (L/H=0.70)

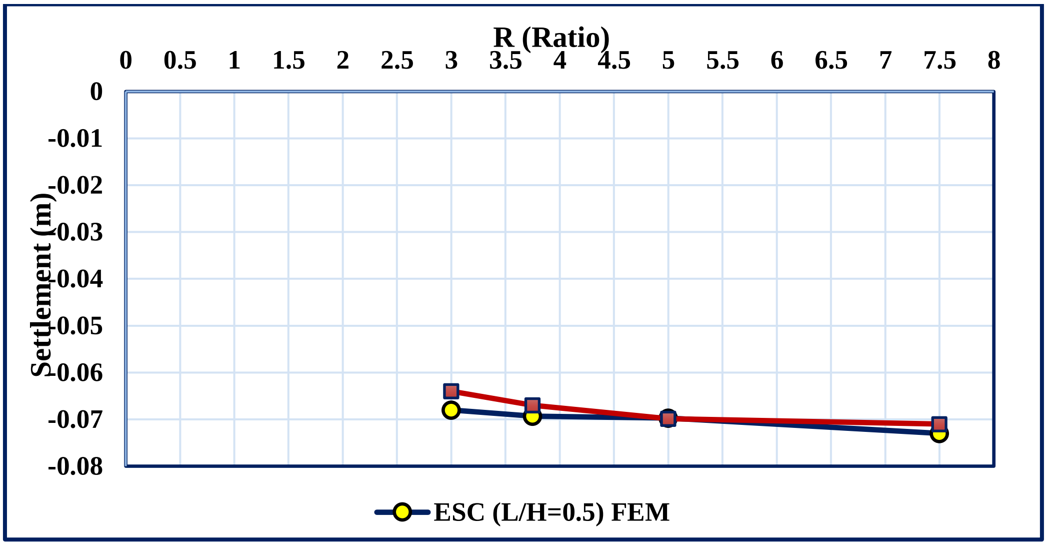


Figure11: Comparison between FEM and analytical solution results in case of floating ESC (L/H=0.50)

6. Conclusion

- The results obtained from the finite element model are in good agreement with the proposed analytical solution.
- Owing to stone column reinforcement, the soft clay performance is improved based on the ratio of R. Thus, by decreasing the ratio of R, the settlement of the soft clay is decreased by ratio 31%, 43%, 51%, and 57% at (R =7.5, 5.0, 3.75, 3.0) respectively.
- The performance of geogrid encased stone column of smaller diameters is superior to that of larger diameter stone columns for the same encasement especially at R=5.0 because of mobilization of higher confining stresses in smaller diameter stone columns. The higher confining stresses in the column leads to higher stiffness of smaller diameter geogrid encased columns.
- The soft clay performance is improved by increasing stone column length ratio and encasement length ratio by the percentage of 30%~90%, and 30%~55% respectively.

Notations

The following Nomenclature, and Abbreviations are used in this paper:

Cu: Cohesion
Ds: Diameter of the influence zone in the axisymmetric unit cell.
Dc: Diameter of the stone column in the unit cell.
R: Diameter ratio
As: Area replacement ratio in axisymmetric unit cell.
T: Time.
S: Center-to-center spacing of the stone column
L: Length of stone column.
EA: Axial stiffness of geogrid

Ψ Dilatancy angle.
Q: Applied load.
E: modulus of elasticity.
Φ: Friction angle.
ν: Poisson’s ratio.
ν_s: Poisson’s ratio of soil
ν_c: Poisson’s ratio of stone column
H: Thickness of clay layer

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