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Research Article

# Numerical Investigation of Ordinary Stone Columns in Soft Soils

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**Abstract** Soft soil deposits are widely speared in some area of Egypt such as: 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 OSC (L/H=1), OSC (L/H=0.7), and OSC (L/H=0.5) installed in soft clay soil using (FEM), and (Analytical Method), 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 finite element method. 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 OSC (L/H=1.0) is better than using OSC (L/H=0.7), and OSC (L/H=0.5). The settlement behavior of clay was improved based on the ratio of 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 improvement, 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 axi 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 OSC (L/H=1), OSC (L/H=0.7), and OSC (L/H=0.5) installed in soft clay soil using (FEM), and (Analytical Method), to determination the improvement factor.

## 2. Numerical Analysis Verification

### 2.1. Ordinary end bearing stone column

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 Ambily (2007) [7]. The tank model he use has a height of 480mm, and diameter of 210 mm of soft clay soil, and with a single stone column of 100 mm diameter. Properties of clay, sand, 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 Fig. (1), and Fig. (2).

**Table 1:** The soil properties which used by Ambily (2007) [7].

| Material | E | Cu | Φ | Ψ | γ |
|---|---|---|---|---|---|
| Clay | 5500 | 30 | 0 | 0 | 0.42 |
| | 3100 | 14 | 0 | 0 | 0.45 |
| Sand | 20000 | 0 | 30 | 4 | 0.30 |
| Stone | 55000 | 0 | 43 | 10 | 0.30 |

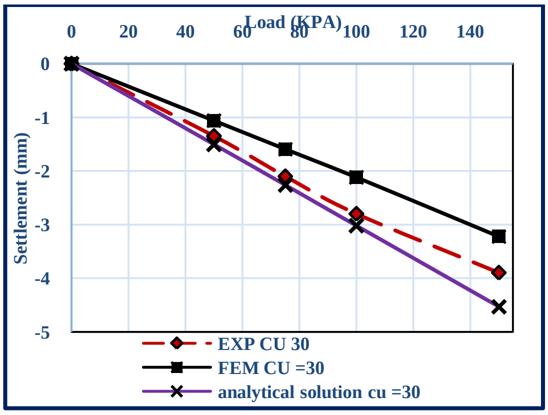


*Figure 1: Verification of FEM with Ambily (2007) Cu=30.*

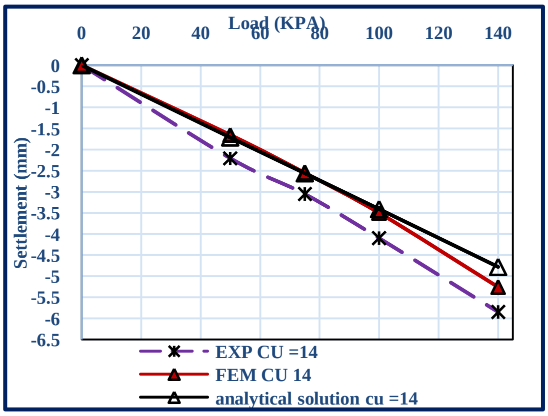


*Figure 2: Verification of FEM with Ambily (2007) Cu=14.*

### 2.2. Ordinary floating stone column

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 Narasimha rao et al (1992) [11]. The test tank is 650 mm diameter and height of clay bed prepared is 350mm. A stone column of diameter 25mm and height 225 mm was made at the center of the clay bed and loaded with a plate of diameter equal to two times diameter of stone column. Properties of clay, and stones are shown in Table 2. 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 Fig. (3).

**Table 2:** The soil properties which used by Narasimha rao et al (1992) [11]

| Material | E | Cu | Φ | Ψ | γ |
|---|---|---|---|---|---|
| Clay | 2000 | 20 | 0 | 0 | 0.45 |
| Stone | 40000 | 0 | 38 | 8 | 0.30 |

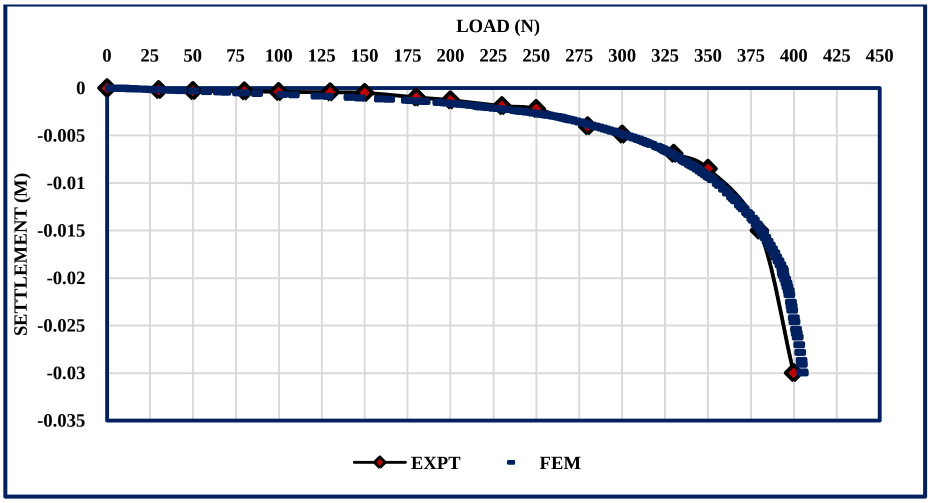


*Figure 3: Verification of FEM with Narasimha rao et al (1992)[11].*

## 3. Design Approaches for Settlement

Reduction of settlement is one of the improvements benefit due to the use of stone columns. The reduction of settlement has been estimated by both pseudo-elastic and elastic plastic methods considering both isolated and wide spread loading using a unit cell concept.

### 3.1. Analytical methods

#### 3.1.1. End bearing ordinary stone columns

The analytical method also offers a very simple realistic engineering approach for estimating the reduction in settlement for improved soil using stone columns.

This paper presents a simple analytical method to estimate the reduction of settlements for soft soil reinforced by stone columns. The used methodology is revealed through the following equations:

$$\text{Settlement} = \frac{Q*H}{EeqClay + Eeq\ Column} \quad (1)$$

Eeq clay +Eeq column = E γ clay (1-As) + E γ column* As (2)

$$E\,\gamma\ \text{clay} = \frac{E}{(1-\gamma\ caly)} \quad (3)$$

$$E\,\gamma\ \text{column} = \frac{E}{(1-\gamma\ column)} \quad (4)$$

As = 0.907(Dc/S) ^2 (5)

Where: Q= Applied load.

E: modulus of elasticity.

H: Thickness of clay layer.

γ: Poisson's ratio.

As: Area replacement ratio in axisymmetric unit cell.

### 3.1.2. Floating ordinary stone columns

This paper presents a simple analytical method to estimate the reduction of settlements for soft soil reinforced by stone columns. The same methodology was adopted, but with some modifications, which includes adding extra equation. The modified methodology can be illustrated through the following equations:

$$\text{Settlement (1)} = \frac{Q*L}{EeqClay + Eeq\ Column} \tag{6}$$

$$\text{Settlement (2)} = \frac{Q*(H-L)}{EeqClay} \tag{7}$$

Settlement Total = Settlement (1) + Settlement (2)

Where: L= Length of stone column.

## 4. Analysis of Stone Column

Plaxis 2D, finite element analysis was carried out for soft clay and for the same clay modified by single stone column (unit cell) under static load for a period of 560-days.The modeling of the single stone column is designed by the axisymmetric pattern in Plaxis 2D. For consolidation analysis, coupled consolidation concept was assumed. 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 single stone column, and untreated soft clay were compared. The properties of soft clay soil and stone column material, beside the geometry data of different diameters and length of stone column are illustrated in Table 3, and Table 4 respectively.

**Table 3:** The properties of soft clay soil and stone column material used in models

| Material | E | Cu | Φ | ψ | γ |
|---|---|---|---|---|---|
| Clay | 2700 | 15 | 0 | 0 | 0.33 |
| Stone | 30000 | 0 | 42 | 12 | 0.30 |

**Table 4:** The geometry data of different diameters and length of the OSC

| Model | H(m) | Ds (m) | Dc(m) | R (Ds/Dc) | L (m) | L/H |
|---|---|---|---|---|---|---|
| OSC 1 | 7.0 | 4.5 | 0.6 | 7.5 | 7.0 | 1.0 |
| OSC 2 | 7.0 | 4.5 | 0.9 | 5.0 | 7.0 | 1.0 |
| OSC 3 | 7.0 | 4.5 | 1.2 | 3.75 | 7.0 | 1.0 |
| OSC 4 | 7.0 | 4.5 | 1.5 | 3.0 | 7.0 | 1.0 |
| OSC 5 | 7.0 | 4.5 | 0.6 | 7.5 | 4.90 | 0.7 |
| OSC 6 | 7.0 | 4.5 | 0.9 | 5.0 | 4.90 | 0.7 |
| OSC 7 | 7.0 | 4.5 | 1.2 | 3.75 | 4.90 | 0.7 |
| OSC 8 | 7.0 | 4.5 | 1.5 | 3.0 | 4.90 | 0.7 |
| OSC 9 | 7.0 | 4.5 | 0.6 | 7.5 | 3.50 | 0.5 |
| OSC 10 | 7.0 | 4.5 | 0.9 | 5.0 | 3.50 | 0.5 |
| OSC 11 | 7.0 | 4.5 | 1.2 | 3.75 | 3.50 | 0.5 |
| OSC 12 | 7.0 | 4.5 | 1.5 | 3.0 | 3.50 | 0.5 |

## 5. Procedure of Analysis

The stone column (unit cell) used to reinforce the soft clay soil was modeled in the finite element analysis, Plaxis 2D, program as shown in Fig. (4).

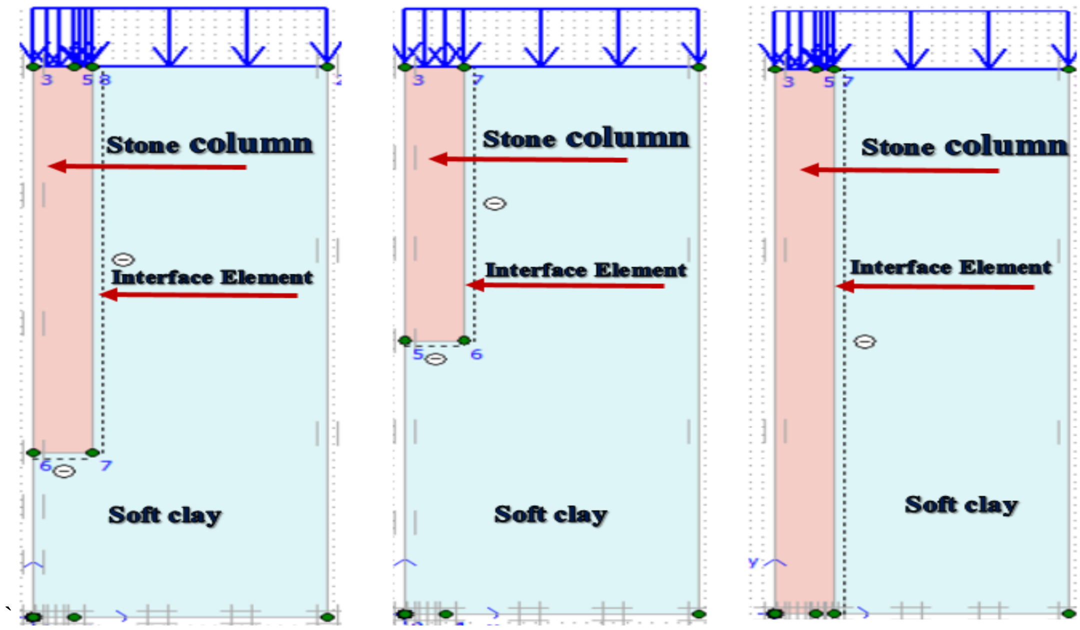


*Figure 4: Unit Cell Stone Column*

## 6. Results and Discussions

### 6.1. Effect of using ordinary stone column

To obtain the effective column length (based on L/H ratio), Twelve FEM models were performed on soft clay soils reinforced with Stone Column with four different ratios of (R = 7.5, 5.0, 3.75, 3.0). Different L/H ratios (L/H = 0.5, 0.70, 1.0) were used. The main aim of those models is to choose the effective L/H ratio of floating OSC compared to end bearing OSC (L/H = 1.0).

Figures 5 to 10 showed that increasing the ratio of column length to the clay deposit thickness leads to significant improvement the settlement of the soft clay soil. As the length of the column increased, the ultimate load carrying capacity increased and the settlement decreased. Based on the results, the settlement curves of the soft clay in case of end bearing OSC with (R = 7.5, 5.0, 3.75, 3.0) is decreased by around 19%, 28%, 39%, and 48%, respectively compared to the settlement curves of soft clay soil, as shown in Fig. (9).

The settlement curves of the soft clay in case of floating OSC (L/H=0.70) with (R = 7.5, 5.0, 3.75, 3.0) is decreased by around 16%, 20%, 23%, and 25%, respectively compared to the settlement curves of soft clay soil, as shown in Fig. (9). The settlement curves of the soft clay soil in case of floating OSC (L/H=0.50) with (R = 7.5, 5.0, 3.75, 3.0) is decreased by around 13%, 14%, 16%, and 17%, respectively compared to the settlement curves of soft clay soil , as shown in Fig. (9).

Based on the results, the settlement curves of the soft clay in case of end bearing OSC with (R = 7.5, 5.0, 3.75, 3.0) is decreased by around 5%, 11%, 28%, and 45%, respectively compared to the settlement curves of the soft clay in case of floating OSC (L/H=0.70), while is decreased by around 10%, 20%, 40%, and 60%, respectively compared to the settlement curves of the soft clay in case of floating OSC (L/H=0.50), as shown in Fig. (10).

The settlement curves of the soft clay in case of floating OSC (L/H=0.70) with (R = 7.5, 5.0, 3.75, 3.0) is decreased by around 2% to 10 % compared to the settlement curves of the softclay in case of floating OSC (L/H=0.50), as shown in Fig. (7 and 8).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.

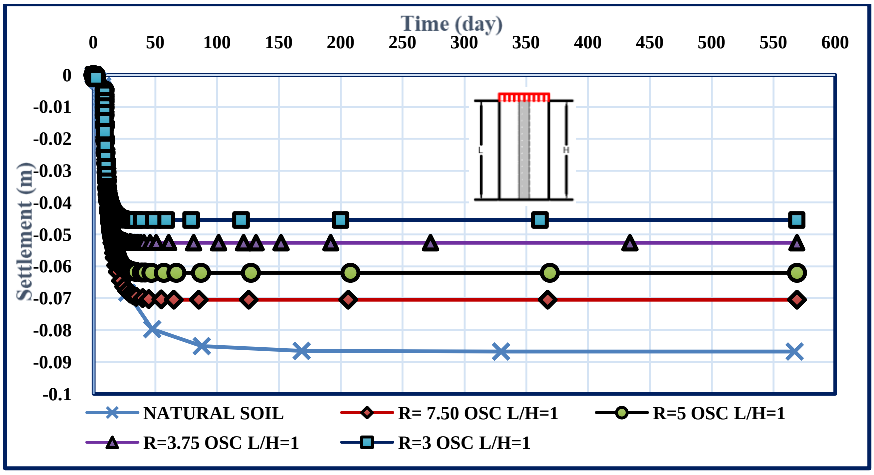


*Figure 5: The influence of the different diameters of the OSC on the settlement behavior in case of (L/ H=1) with (R =7.5, 5.0, 3.75, 3.0)*

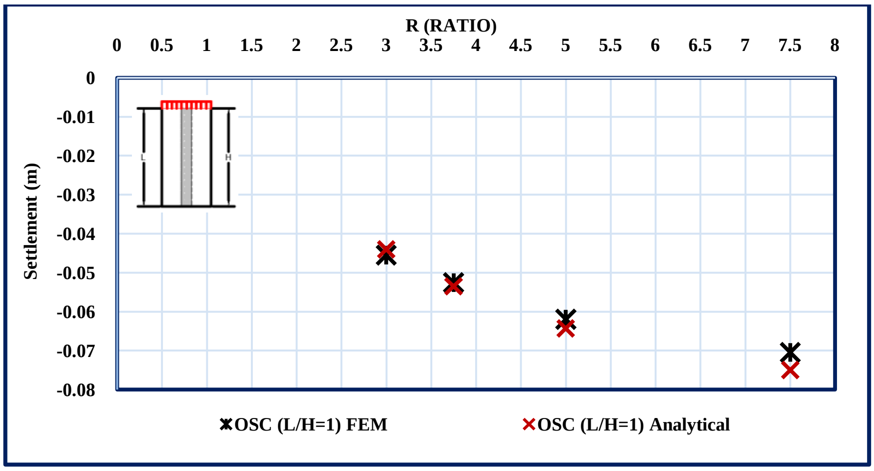


*Figure 6: Effect of the ratio of (R) of the OSC on the settlement behavior in case of (L/H=1.0) (FEM, and Analytical)*

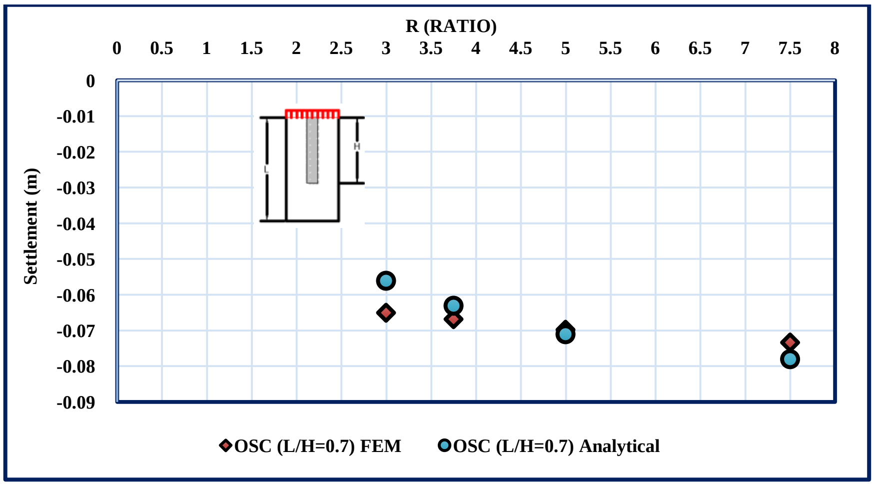


*Figure 7: Effect of the ratio of (R) of the OSC on the settlement behavior in case of (L/H=0.7) (FEM, and Analytical)*

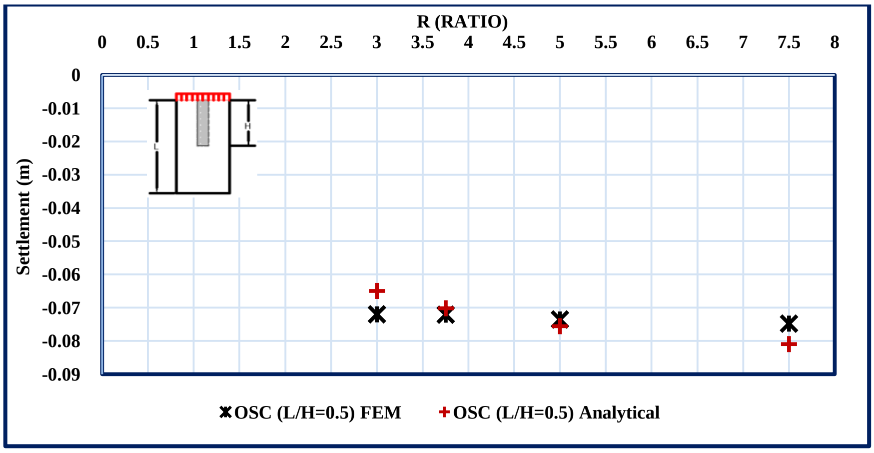


*Figure 8: Effect of the ratio of (R) of the OSC on the settlement behavior in case of (L/H=0.5) (FEM, and Analytical)*

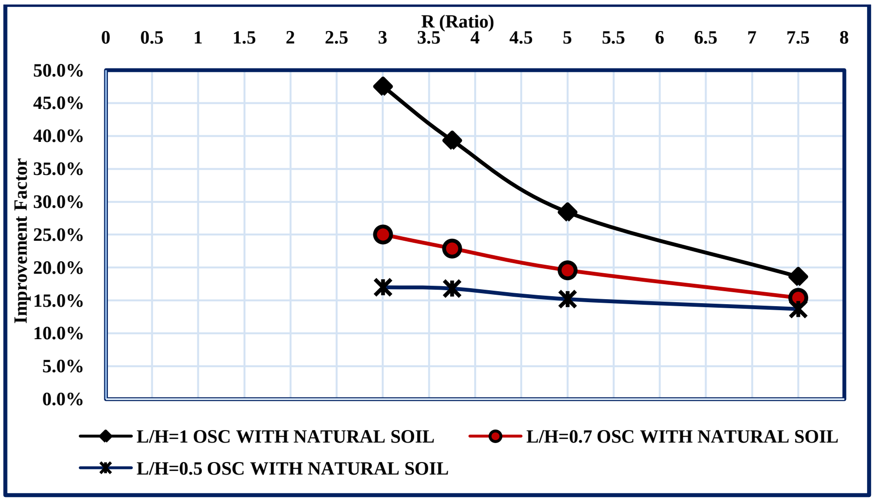


*Figure 9: Effect of the ratio of (R) of the OSC in case of (L/H=1, L/H=0.7, and L/H=0.5) with natural soil on improvement factor*

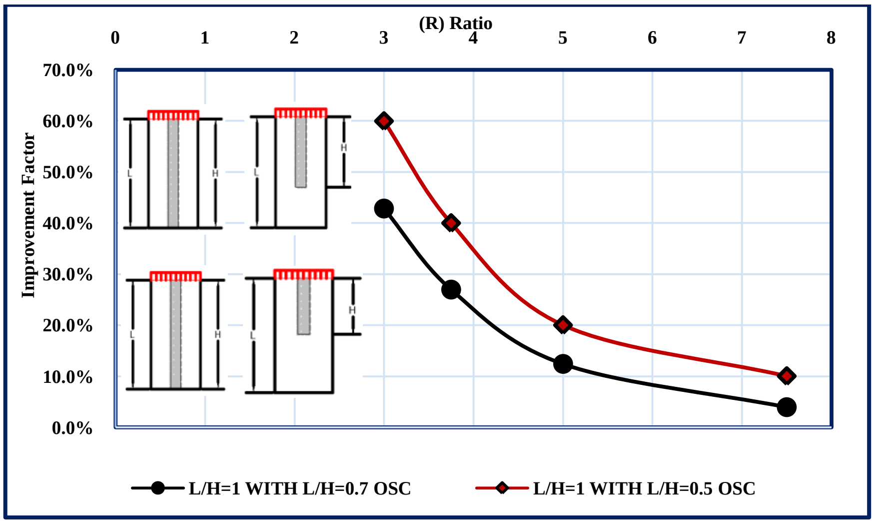


*Figure10: Effect of the ratio of (R) of the OSC in case of (L/H=1 with L/H=0.7, and L/H=1 with L/H=0.5) on improvement factor*

**Table 5:** The maximum displacement of the OSC with (R =7.5, 5.0, 3.75, 3.0)

| R (Ratio) | L/H | Settlement (m) (FEM) | Settlement (m) (Analytical solution) |
|---|---|---|---|
| 7.50 | 1.0 | -0.0705 | -0.075 |
| 5.0 | 1.0 | -0.062 | -0.0643 |
| 3.75 | 1.0 | -0.0526 | -0.0535 |
| 3.0 | 1.0 | -0.0455 | -0.044 |
| 7.5 | 0.7 | -0.0733 | -0.078 |
| 5.0 | 0.7 | -0.0697 | -0.071 |
| 3.75 | 0.7 | -0.0668 | -0.063 |
| 3.0 | 0.7 | -0.065 | -0.056 |
| 7.5 | 0.5 | -0.0748 | -0.081 |
| 5.0 | 0.5 | -0.0735 | -0.0756 |
| 3.75 | 0.5 | -0.0721 | -0.0702 |
| 3.0 | 0.5 | -0.072 | -0.065 |

## 7. **Conclusions**

1) Owing to stone column reinforcement, the settlement behavior of clay was improved based on the ratio of R. Thus, by decreasing the ratio of R, with consideration of the end bearing stone column, the settlement of the soft clay was decreased.
2) Stone column plays two influential roles in the soft cohesive soil: a) as a part of the soil, it improves the settlement behavior of the soft soil, b) stone column behaves like drain wells and accelerates the consolidation process.
3) 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.
4) The settlement curves of the soft clay in case of end bearing OSC with (R = 7.5 , 5.0 , 3.75, 3.0) is decreased by around 19%, 28%, 39%, and 48%, respectively compared to the settlement curves of soft clay soil.
5) The settlement curves of the soft clay in case of floating OSC (L/H=0.70) with (R = 7.5, 5.0, 3.75, 3.0) is decreased by around 16%, 20%, 23%, and 25%, respectively compared to the settlement curves of soft clay soil.
6) The settlement curves of the soft clay soil in case of floating OSC (L/H=0.50) with (R = 7.5, 5.0, 3.75, 3.0) is decreased by around 13%, 14%, 16%, and 17%, respectively compared to the settlement curves of soft clay soil.
7) The settlement curves of the soft clay in case of end bearing OSC with (R = 7.5, 5.0, 3.75, 3.0) is decreased by around 5%, 11%, 28%, and 45%, respectively compared to the settlement curves of the soft clay in case of floating OSC (L/H=0.70), while is decreased by around 10%, 20%, 40%, and 60%, respectively compared to the settlement curves of the soft clay in case of floating OSC (L/H=0.50).
8) The settlement curves of the soft clay in case of floating OSC (L/H=0.70) with (R = 7.5, 5.0, 3.75, 3.0) is decreased by around 2% to 10 % compared to the settlement curves of the soft clay in case of floating OSC (L/H=0.50).

## 8. Notation

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.
As: Area replacement ratio in axisymmetric unit cell.
R: Diameter ratio.
T: Time.
S: Center-to-center spacing of the stone column
OSC: Ordinary Stone Columns.
ESC: Encased Stone Columns.
Ψ: Dilatancy angle.
Q: Applied load.
E: modulus of elasticity.
Φ: Friction angle.
X: Length of encasement.
γ: Poisson's ratio.
L: Length of stone column.

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