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Investigation of the Effect of Dimensional Characteristics of Stone Column on Load-Bearing Capacity and Consolidation Time

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Abstract

One of the best methods for rehabilitating loos and soft soils is the application of stone columns. This method enhances the soil properties by increasing its load-bearing capacity, decreasing the soil subsidence, and accelerating the consolidation rate. In the present paper, numerical analysis of a stone column of 10 m in length into a clayey soil using ABAQUS software is presented. The stone column was modelled based on the concept of unit cell, i.e. a single stone column with the surrounding soil. In this respect, material of the stone column was modelled using the elastoplastic behavioural model of Mohr-Coulomb, while Cam Clay behavioural model was used for the surrounding clayey soil. Furthermore, throughout the analyses performed in this study, effects of different parameters (e.g. applied load on rigid foundation, and the stone column length and diameter) on the subsidence and consolidation time of the rigid foundation were examined. The results indicated that, construction of a stone column into clayey soil decreases the subsidence and consolidation time of the soil considerably. In additions, increases in length and diameter of the stone column were found to significantly contribute to reduced subsidence and consolidation time of soil.

Keywords: Stone Column; Consolidation; Load-Bearing Capacity; Subsidence; ABAQUS.

1. Introduction

Construction of stone columns serves as an effective, economic, and environmentally friendly approach to rehabilitation of the grounds composed of cohesive and non-cohesive loos soils. For many years, the method has been in use for reducing subsidence, enhancing load-bearing capacity, decreasing soil liquefaction, and accelerating consolidation of loos and marshy soil. The stone column also contributes to vertical drainage of the soil, thereby accelerating the soil consolidation process. By replacing soft soil with rubble stones (which are compacted during the course of the replacement process), specific gravity of the soil increases practically while the soil porosity experiences a decrease.

For more than 50 years, deep vibrators have been used to enhance load-bearing capacity and subsidence properties of weak soils. Since 1938, methods and equipment items have been developed for compacting non-cohesive soils for construction at depths beyond 18 m, ending up with excellent results. Currently, this innovative method is referred to as vibro compaction and has been successfully implemented around the world. Today, stone columns are constructed via two major methods, which together are referred to as vibro techniques. The methods include vibro compaction and vibro replacement [1].

Construction of stone columns in cohesive soils includes the replacement of some portion of inappropriate soil with a

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column of well-compacted suitable stone material. In this technique, a borehole is drilled by penetrating a deep vibrator, and while the vibrator is being pulled out of the borehole, suitable stone material are loaded into the borehole and compacted. In saturated soils, a jet of water is employed to have the vibrator penetrated into the borehole, and the vibrator leaves the borehole completely or partially before loading the borehole with stone material and compacting the material. This method is known as wet tip feed. The water jet is not used in under-saturated and collapsible soils, where an air jet is sometimes used to accelerate the penetration process. In such cases, as the vibrator is leaving the borehole, stone materials are loaded into the borehole via a pipeline connected to the vibrator followed by compaction. This latter method is referred to as dry bottom method. The two methods have been used to construct stone columns into coastal soils since 1950.

Performing local studies, Bergado et al. found that, application of stone columns enhances load-bearing capacity and roof safety factor by 400% and 25%, respectively [2]. Moreover, Priebe (1995) presented a method for estimating the subsidence of a foundation constructed on an infinite mesh of stone columns. In this method, the area of the soil surrounding the columns and affected by only one particular stone column was considered as a circle with its diameter depending on the column spacing, i.e. a cylinder of soft soil with the stone column at its center. The area was used to model the behavior of the stone column within its effective range. The set of the soft soil cylinder with equivalent circular section and the stone column at its center was introduced as unit cell [1].

Numerically analyzing different groups of stone column, Castro (2014) found that, for a given stone material replacement ratio, an increase in the number of stone columns or a change in the configuration of stone column group imposed no impact on the subsidence of the rehabilitated foundation [3]. Frikha et al. (2014) used physical model of rehabilitated clayey soil with different groups of stone column to investigate the effect of the number and spacing of sandy stone columns on the subsidence and consolidation time. They showed that, by increasing the number and reducing the spacing of sand stone columns, consolidation subsidence time decreases significantly [4].

Applying a geotextile frame around a stone column, Miranda et al. (2017) demonstrated that, the application of geotextile can lower the subsidence and consolidation time of rehabilitated soil with stone column [5]. Investigating the studies performed on stone columns, Babu et al. (2013) concluded that the application of stone column in very soft soils tends to attenuate load-bearing capacity of the stone column [6]. Focusing on the soil rehabilitated with a single stone column, Fathi et al. (2015) showed that, application of stone column decreases effective vertical stress in clayey soils [7]. Shahu et al. (2011) undertook physical and numerical modeling of stone column groups and indicated that, the most effective parameters on soil rehabilitation with stone column include the replacement ratio of clayey soil with stone material and length-to-diameter ratio of the stone column [8].

Tan et al. (2014) examined the influence of increasing suspended stone column length on reducing the subsidence and consolidation time. Based on their results, it was revealed that, an increase in stone column length decreases the drainage spacing, thereby accelerating the consolidation subsidence. It was further found that, an increase in the stone column length further limits the consolidation subsidence at higher replacement ratios [9]. Fattah et al. (2017) studied a number of physical model of suspended stone columns into soil to examine load-bearing capacity of suspended stone columns. Results of their research were presented in the form a relationship for the capacity of suspended stone column [10].

Marandi et al. (2016) looked into the impact of strength parameters of stone material on stability coefficient of embankment constructed on rehabilitated clayey soil with stone column. In this research, equivalent region method was used to numerically model the soil rehabilitated with stone column. In the equivalent region method, the entire set of clayey soil and stone column is modeled as a single region with equivalent strength properties [11]. Yu (2015) investigated the effect of geosynthetics around stone column. In this modeling, a stone column group below an embankment was studied. Results of the research indicated that, application of geosynthetics around stone column accelerates consolidation subsidence of the rehabilitated soil while enhancing load-bearing capacity of the stone column [12].

Using physical and numerical models, Mohanty and Samanta (2015) investigated load-bearing capacity of soil rehabilitated with stone column. Accordingly, it was found that, behavior of stone column in the soil is largely dependent on the thickness and physical properties of the first layer of soil [13]. In the present paper, impacts of stone column length and diameter on the subsidence and consolidation time of saturated clayey soil were considered. For this purpose, numerical model of a stone column was prepared via finite-element (FE) analysis, and by comparing the modeling results with available data in the literature for a given problem, accuracy and precision of the model were evaluated. Once finished with verifying the model, it was employed to undertake parametric study of the effects of stone column length and diameter on the subsidence and consolidation time of soft clayey soils.

2. Material and Methods

Design of suspended stone column is performed following relevant procedures based on consolidation subsidence of rehabilitated and non-rehabilitated layers. Reave and Ranjan (1985) presented a simple methodology for calculating the subsidence of a rehabilitated foundation with suspended stone column [14].

Japan Institute of Construction Engineering (JICE) (1999) proposed a method for calculating consolidation subsidence of rehabilitated soil with stone column where stone material replacement ratio was $\alpha < 0.3$ (where $\alpha = A_c / A$, A = total influence area, and A_c = area of column). According to this procedure, subsidence is equal to the subsidence of non-rehabilitated layer plus 33% of the subsidence of non-rehabilitated soil layer with a length equal to that of the stone column [15].

Chai et al. (2009) proposed a method where equivalent length of non-rehabilitated layer (H_c) was obtained from the length of rehabilitated layer (H_L), replacement ratio (α), and the ratio of column length to total length of the soil layer (β) [16].

$$H_c = H_L . f(\alpha) . g(\beta)$$

$$f(\alpha) = \begin{cases} 0.533\text{-}0.013\alpha & (10\% \le \alpha \le 40\%) \\ 0 & (40\% < \alpha) \end{cases}$$

$$g(\beta) = \begin{cases} 1.62\text{-}0.016\beta & (20\% \le \beta \le 70\%) \\ 0.5 & (70\% \le \beta \le 90\%) \end{cases}$$

In this evaluation, modeling and all analyses were performed utilizing ABAQUS, a FE software. Considering the theories presented on the use of unit cell to model stone column conditions, the present study adopts the idea of unit cell for modeling. In modeling via unit cell method, it is assumed that a large area of soil is rehabilitated by a large number of stone columns, where a single stone column together with the surrounding soil are modeled as a cylinder. Load was completely applied to the stone column and surrounding soil via a rigid foundation. Boundaries of the unit cell are assumed to experience no displacement, shear stress, or flow.

On this basis, in order to reduce the processing load and simplify the numerical modeling, two-dimensional modeling with axisymmetric conditions was used, so that half of a longitudinal section crossing vertical axis of the unit cell cylinder was modeled rather than the whole system (Figure 1) [17]. Considering the problem specifications, two-dimensional, axisymmetric FE numerical modeling was used in this study.

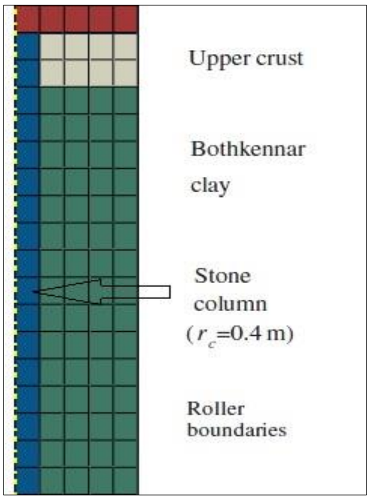

Figure 1. A view of meshing of the numerical model

In this model, radius of the sample unit cell is fixed at 2 m. Height of clayey soil is assumed to be 10 m. The entire system of soil and stone column are assumed to be saturated, with the load applied to the soil and stone column instantaneously and under undrained conditions via a rigid foundation with a diameter equal to the unit cell [18].

Tie constraints were used for all contact surfaces, including the contact surface between stone column and clayey soil and that between rigid foundation and soil and stone column [8]. Regarding boundary conditions, lateral sides of the model along X-axis and bottom of the model along X and Y axes were constrained, and pore water flow was presumably drained from top of the model only. As is clear in Figure 1, the soil was modelled as two layers: clayey soil and stone column materials. Material of the stone column was modelled using the elastoplastic behavioural model of Mohr-Coulomb, while Cam Clay behavioural model was used for the surrounding clayey soil. Specifications considered for the material are reported in Tables 1 and 2, where γ is specific gravity, e is porosity ratio, OCR is pre-consolidation ratio, POP is pre-loading pressure, K_0 is the coefficient of lateral earth pressure, κ is the slope of repeated loading-unloading curve in the e – lnp plane, ν is Poisson's ratio, λ is the slope of normally consolidated line, M is the slope of critical line, K is permeability, C is cohesion, E is the modulus of elasticity, φ is internal friction angle of soil, and ψ is dilation angle.

Table 1. Specifications of the materials composing the two layers of clayey soil

Materials	γ (kN/m^3)	e_0	OCR	PoP (KPa)	K_0	κ	ν	λ	M	K (m/day)
Clay 0-1	18	1.1	-	30	1.35	0.02	0.2	0.48	1.4	**7e-5**
Clay 1-10	16.5	2	1.5	-	0.544	0.02	0.2	0.48	1.4	**7e-5**

Table 2. Specifications of the materials composing stone column and rigid foundation

Materials	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	C (KPa)	φ	ψ	ν	E (MPa)	K (m/day)
Stone Column	16	19	0.1	42	12	0.2	35	1.7
Concrete foundation	24	-	-	-	-	0.15	3000	-

Figure 2 demonstrates the equipment required for installing stone column via vibro-displacement method, which is a common technique for installing stone columns into earth [19].

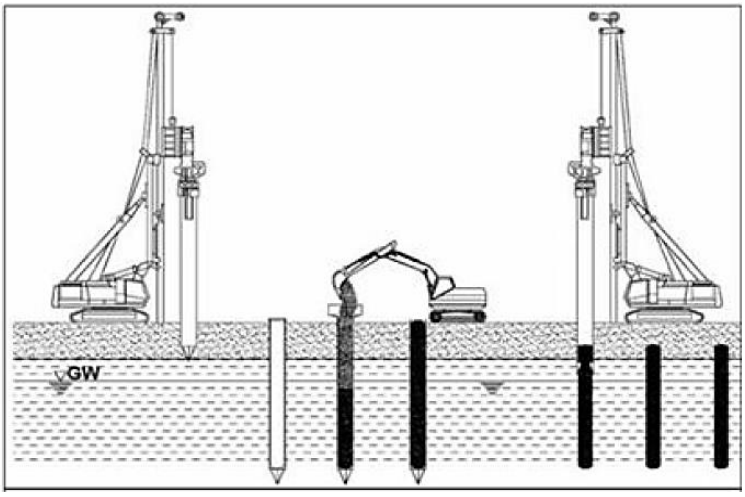

Figure 2. A view of different steps of installing stone columns via vibro-displacement technique

Different models of stone column were created by changing stone material replacement ratio and stone column height, and the results were compared

3. Verification of the Numerical Model

Narasimho et al. (1992) obtained load-subsidence curve for a system of soil mass with a height of 350 mm and diameter of 650 mm equipped with a single stone column with a length of 225 mm and diameter of 50 mm in the middle of the soil mass. For this purpose, they build an experimental model and subjected to loading using a rigid plate of 100 mm in diameter until rapture. Properties of the materials used in this study are reported in Table 3. The formulated numerical model was used to simulate this physical model, with the results compared in Figure 3. The research performed by Narasimho et al. on a physical model of a single stone column beneath a rigid foundation in soft clayey soil indicated no displacement along the lower and right hand-side boundaries of the model, while the left hand-side boundary exhibited displacements along vertical direction; these were carefully incorporated into the numerical modeling. In order to verify the modeling, the loading-subsidence curve obtained from the numerical modeling was compared to that of the physical model built in laboratory. Closeness of the results verified accuracy of the prepared numerical model [20]. As pore water pressure was not taken into consideration, the subsidence investigated in the verification stage was instantaneous subsidence.

Table 3. Material properties used by Narasimho et al. (1992)

Materials	C (KPa)	φ	v	E (MPa)
Stone Column	0	38	0.3	45
Clay	20	0	0.45	4

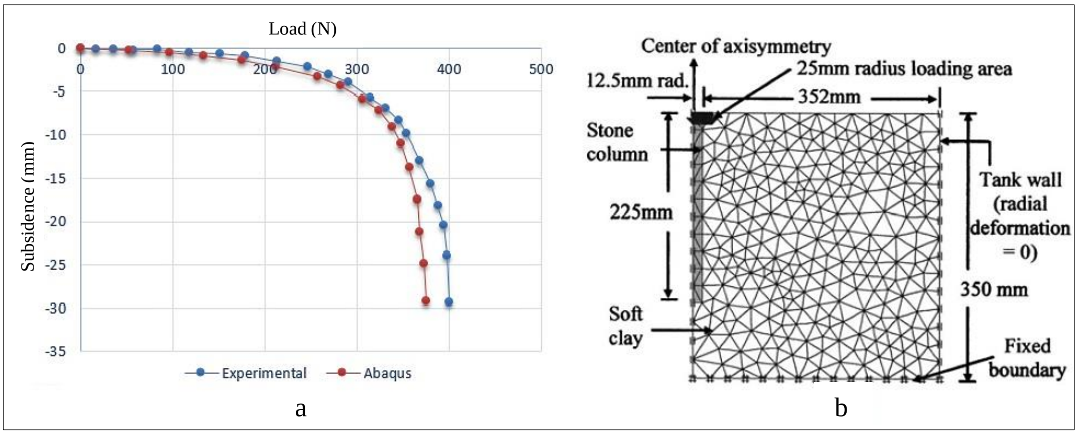

Figure 3. Comparison between the presented numerical model and the physical model proposed by Narasimho et al. (1992); (a) comparison results; (b) geometry and dimensions

4. Results of Numerical Modeling

Given that accuracy of the developed numerical model was verified, the model was used to study the effect of different parameters on consolidation subsidence of soil; the parameters included stone column length and diameter. For this purpose, in each stage, one of the parameters was varied while keeping constant all other parameters.

4.1. Effect of Stone Column Length

According to Mitra and Chattopadhyay (1999), before axial stresses can be fully distributed over a stone column, minimum stone column length-to-diameter ratio shall be 4.5 [21], and given that the stone column diameter considered in the model is 80 cm, its length was considered to range between 4 m and 10 m.

Based on the research by Castro et al. (2014), loading-subsidence curve for the non-rehabilitated clayey soil used in the model can be seen in Figure 4.

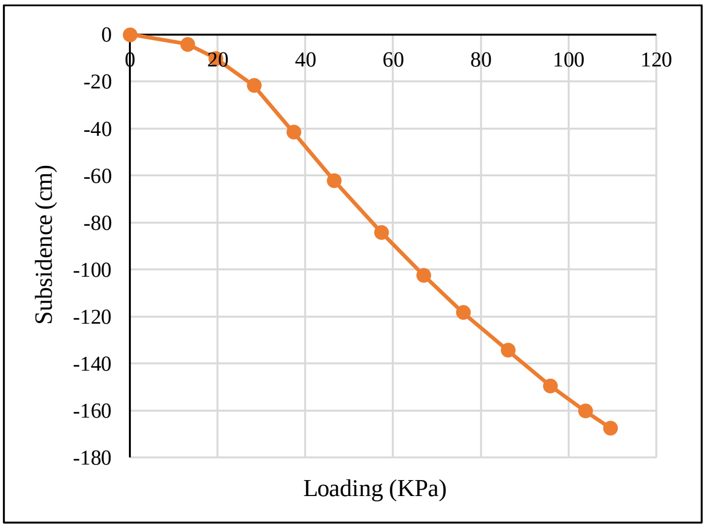

Figure 4. Loading-subsidence curve for the non-rehabilitated clayey soil used in the model presented by Castro et al. (2014)

Figure 5 shows the plot of subsidence versus time for a stone column of 40 cm in radius and a unit cell radius-to-stone column radius ratio of 5. In this figure, length of the stone column is varied from 4 to 10 m, while all other parameters were kept unchanged. The pressure applied to the rigid foundation is 44 kPa. In Figure 6, the applied load is doubled to see the impact of the stone column length on the consolidation rate and subsidence.

As can be observed, with increasing the stone column length, the consolidation process accelerated due to shorter water drainage length in the clayey soil, and thanks to higher strength parameters of the stone column material compared to those of clayey soil, at least 50 cm lower subsidence was observed than that experienced with non-rehabilitated soil. It is observed that, the increase in stone column length from 4 to 10 m decreases the consolidation time by 90% and the subsidence by 10%. Nevertheless, given that lateral distance of the farthest point of the model to the surface of the stone column is 2 m, an increase in the stone column length from 8 to 10 m induced no significant change in the consolidation time because of the fixed lateral distance and reduction of the longitudinal distance to the model base from 2 m to zero, i.e. the longest drainage distance remained practically unchanged. Moreover, it can be seen that, with increasing the length from 6 to 8 m, load-bearing capacity remained almost unchanged, but once the column length was increased from 4 to 6 m and from 8 to 10 m, load-bearing capacity of the foundation improved, because the increase in stone column length from 4 to 6 m leads to complete distribution of axial stresses on the stone column, and the increase in the column length to 10 m brings in contact the stone column with the bed rock assumed at the depth of 10 m, thereby directly transmitting the load from foundation to the bed rock.

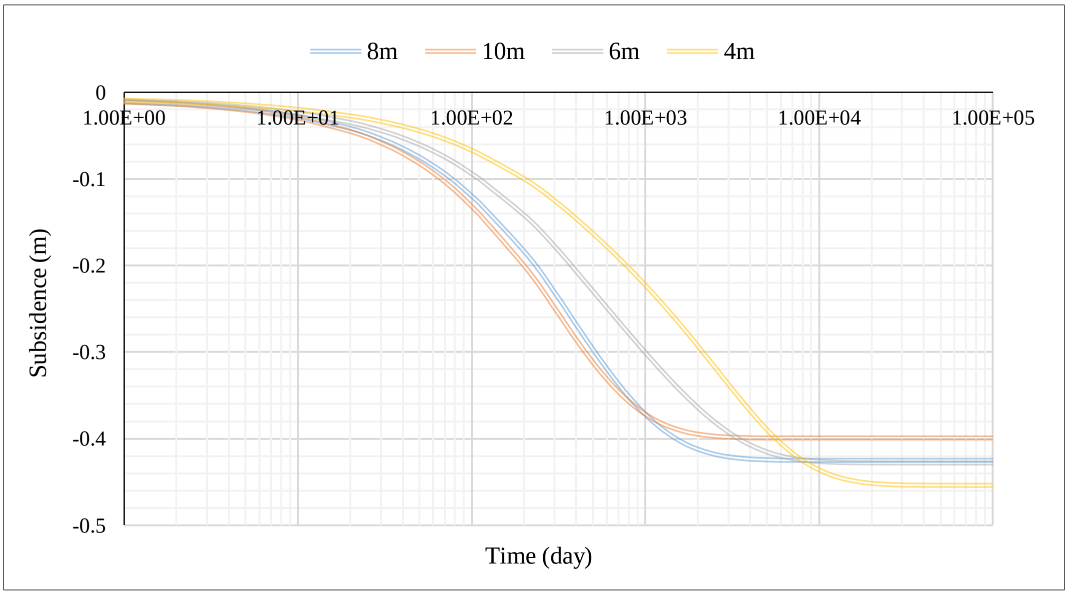

Figure 5. Plot of subsidence for an applied load of 44 kPa, unit cell radius-to-stone column radius ratio of 5, and different stone column lengths

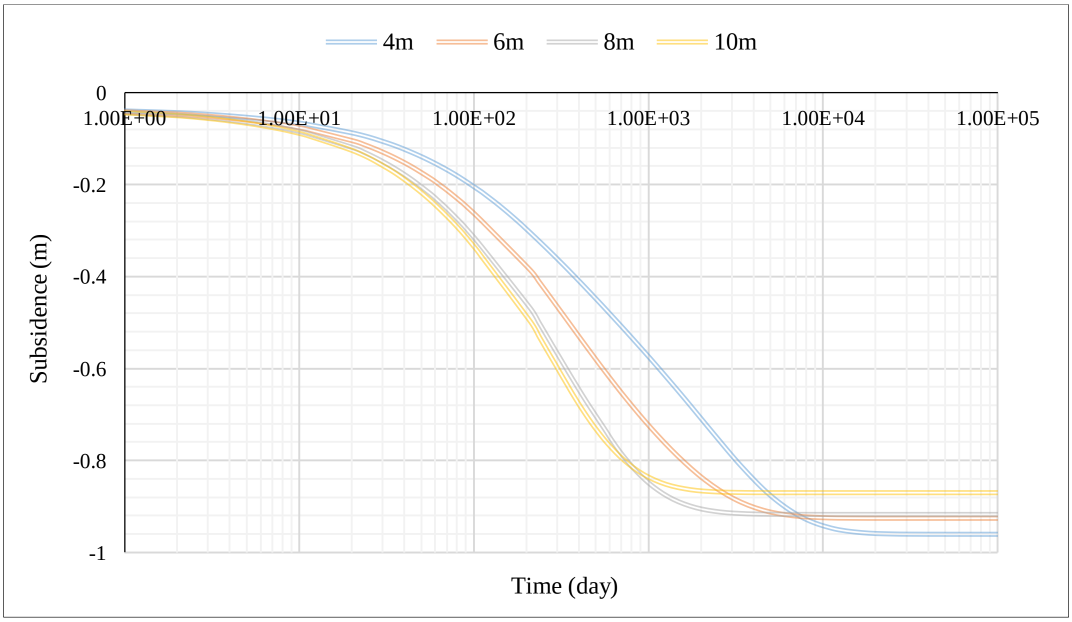

Figure 6. Plot of subsidence for an applied load of 88 kPa, unit cell radius-to-stone column radius ratio of 5, and different stone column lengths

Presented in Figure 7 are contours of pore water pressure for stone columns of different lengths from 4 to 10 m. In this figure, it is observed that, with increasing the stone column length, the length of water drainage area extends, so that pore water pressure decreases at a faster rate.

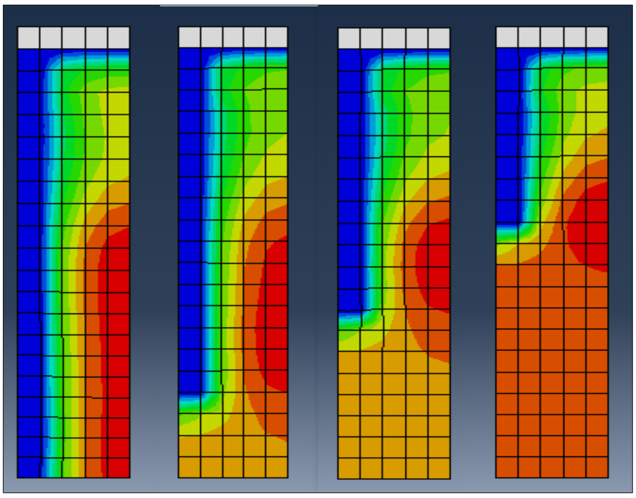

Figure 7. Contours of pore water pressure for stone columns of different lengths after 10 days of the start of loading

Plot of the effect of increased stone column length on the reduction of rehabilitated soil was developed using the consolidation subsidence of the non-rehabilitated soil. Figure 8 demonstrates the ratio of subsidence in rehabilitated soil to that in non-rehabilitated soil. Accordingly, it is observed that, an increase in the stone column length from 4 m to 10 m lowers the consolidation subsidence by 10%.

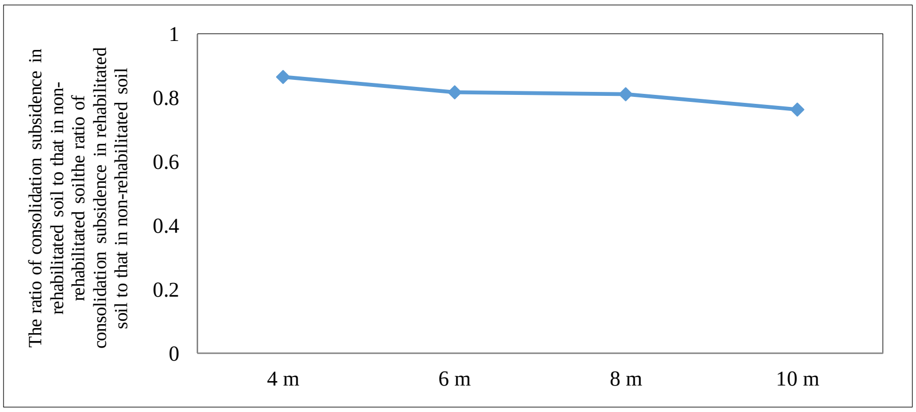

Figure 8. Variations of consolidation subsidence ratio for stone columns of different lengths

In Figure 9, calculating the required time to achieve 90% of the consolidation subsidence, the required times for consolidation subsidence with stone columns of different lengths are compared. In this purpose, the ratio of consolidation subsidence time for rehabilitated soil to that for non-rehabilitated is used. The figure reveals considerable effect of an increase in the length of stone column on the reduction of consolidation subsidence time.

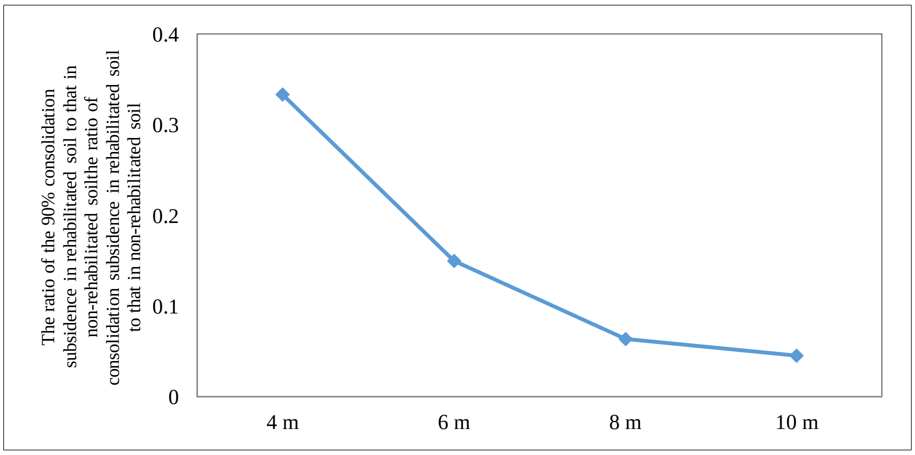

Figure 10. Variations of 90% consolidation subsidence ratio for stone columns of different lengths

4.2. Effect of Stone Column Diameter

Continuing with the research, keeping constant the stone column length and the applied load to the rigid foundation, the stone column diameter was increased to see the effect of this parameter on the subsidence and consolidation time of the rigid foundation. For this purpose, unit cell radius was fixed at 2 m, the ratio of unit cell radius to stone column radius was increased from 3 to 5m the stone column length was fixed at 10 m, and 44 kPa of load was applied to the foundation, with the results shown on Figure 11.

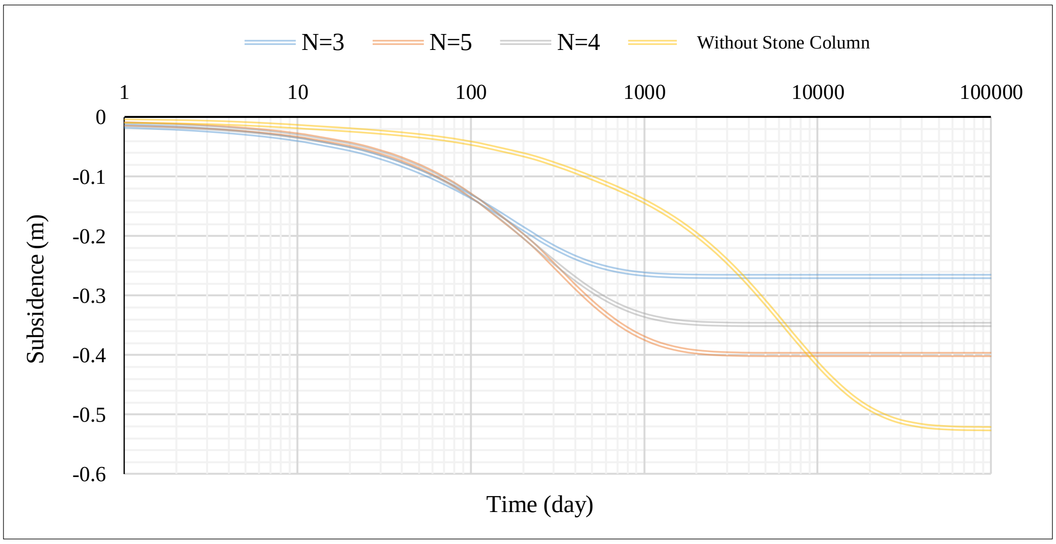

Figure 11. Plot of subsidence for an applied load of 44 kPa, for different unit cell radius-to-stone column radius ratios

As can be observed, upon increasing the stone column diameter, the foundation subsidence and consolidation time decreased significantly. Occurred due to replacement of loos soil with strong material, this subsidence was almost proportional to the fraction of soil replaced with stone column material. Also, Figure 4 shows the foundation subsidence when constructed on soil with no stone column. As can be seen, construction of stone column imposes large contributions into rehabilitation of loos soil and lowers the subsidence and consolidation time remarkably. Figure 12 presents stress contours for stone columns of various diameters. The figure shows that, with increasing the stone column diameter, drainage spacing decreases.

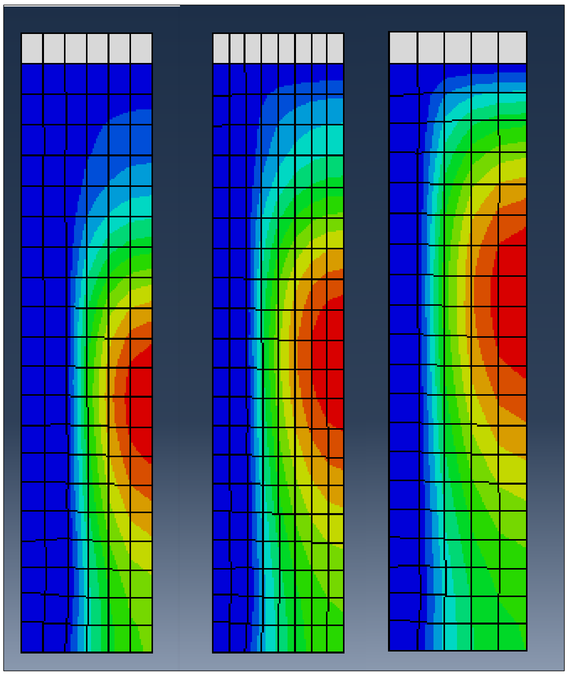

Figure 12. Contours of pore water pressure for stone columns of different diameters after 400 days of the start of loading

Figures 13 and 14 present the effect of an increase in stone column diameter on the reduction of subsidence and consolidation time. The figures indicate that, the stone column diameter imposes larger impacts on the subsidence and consolidation time.

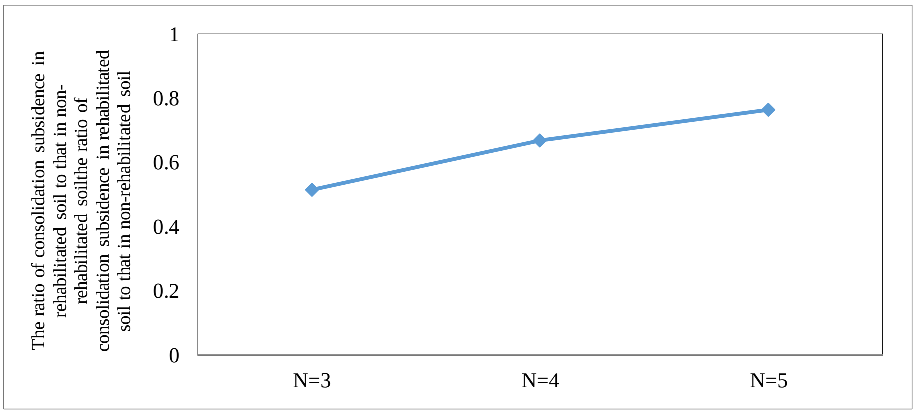

Figure 13. Variations of consolidation subsidence for stone columns of different diameters

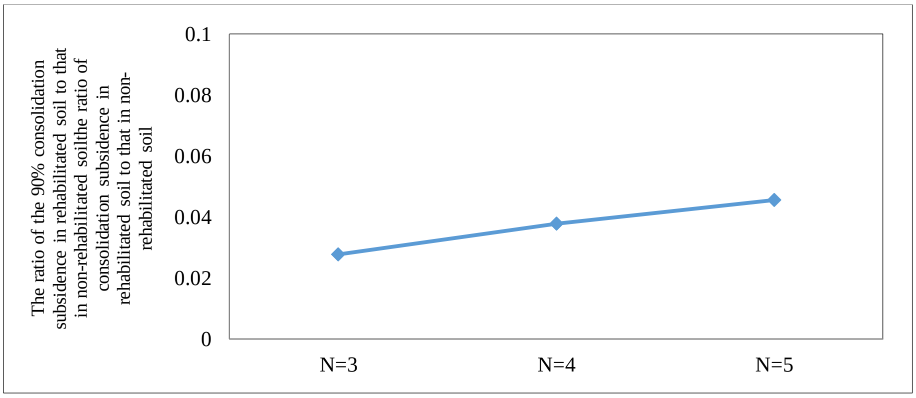

Figure 14. Variations of 90% consolidation subsidence time for stone columns of different diameters

5. Conclusion

Rehabilitation of soft clayey soil using stone columns enhances load-bearing capacity while reducing consolidation time and subsidence of the soil. It was observed that, an increase in stone column length at a given replacement ratio imposed significant effects on the reduction of soil subsidence time. In the meantime, it should be noted that, in cases where the increase in stone column length fails to reduce drainage spacing of clayey soil, it will not reduce the consolidation rate significantly. It was further observed that, in contrary to the effect of increased stone column length, an increase in the diameter of the stone column significantly decreased the soil subsidence. The reason behind this decrease is the replacement of loos soil with stronger material.

Based on the results of the present study, it is recommended to choose dimensions of stone column in such a way to minimize construction costs while maximizing performance of the stone column for the particular project in hand.

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