SETTLEMENT EVALUATION OF SOFT CLAY REINFORCED BY STONE COLUMNS, CONSIDERING THE EFFECT OF SOIL COMPACTION

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ABSTRACT

This paper investigates the performance of stone columns in soft clay. Finite element analyses were carried out to evaluate settlement of soft clay reinforced with stone columns using 15-noded triangular elements using Plaxis software. A drained analysis was carried out using Mohr-Coulomb's criterion for soft clay, stones, and sand. At the interface between the stone column and soft clay, interface elements have been used. The column installation was simulated for calculating the stresses due to compaction of soil. From numerical results, coefficient of lateral earth pressure after the installation of stone column and the settlement reduction ratio (*SRR*) of the soil has been estimated. On the bases of this analysis, variation of stress in soft soil after installation of column with distance from column is significantly reduced. The results are compared with those available in the literature and the advantages of the numerical analysis were highlighted.

Keywords: *Settlement reduction ratio, Stone column, Finite element method, Area replacement percent.*

1. INTRODUCTION

The existing soil on a given site may not be suitable for supporting the desired facilities such as buildings, bridges, dams and so on because safe bearing capacity of a soil may not be adequate to support the given load. To improve these soil types to allow building and other heavy construction, it is necessary to create stiff reinforcing elements in the soil mass. A number of these techniques have been developed in the last fifty years. The mechanics of ground improvement depends largely on the type of soil. A method for increase of strength is the incorporation into a weak foundation soil of cylindrical inclusions (columns) made up of a material having higher strength characteristics, will obviously result in an increase of its bearing capacity. Considering for instance a soft clay with a relatively low shear strength, two kinds of column reinforcement techniques might be envisaged: the 'stone column' technique which consists in introducing within the soft clay a vibrocompacted stone or ballast material, the friction angle of which may exceed 40 and the 'lime column' technique obtained from mixing the weak soil mass with a given percentage of lime or lime–cement, thus producing a considerable increase of the soil initial shear strength (up to 20 times), together with a relatively small friction angle[1].The stone column technique, also known as vibro-replacement or vibro-displacement, is a ground improvement process where vertical columns of compacted aggregate are formed through the soils to be improved. These columns result in considerable vertical load carrying capacity and improved shear resistance in the soil mass.

Stone columns are installed with specialized vibratory probes. The vibrator first penetrates to the required depth by vibration and air or water jetting or by vibration alone. Gravel is then added at the tip of the vibrator and progressive raising and repenetration of the vibrator results in the gravel being pushed into the surrounding soil. The installation of stone column is accompanied by vibration and horizontal displacement of soil. Many of the researchers for considering horizontal displacement of soil during the installation of stone column, post-installation coefficient of earth pressure, k^*, considered more than k_0, where k_0 is coefficient of lateral earth pressure at rest [2, 3-5]. Elshazly et.al [6] presented the interesting relation between the inter-column spacing and k^* in vibro-installation technique. This relation was inferred from analyses for load settlement records of various field load tests, performed for stone columns arrangements with different inter-column spacing values. A well-documented case history, involving three columns' patterns along with their relevant field and laboratory test results, was utilized for this study. Moreover, a well-tested-coupled finite element model was employed in the analysis. The analysis is inversely posed to determine the soil initial stresses, based on the recorded settlements and the post-installation material properties.

Many of the researchers have developed theoretical solutions for estimating bearing capacity and settlement of reinforced foundations by stone columns [8-10]. Priebe [2] proposed a method to estimate the settlement of foundation resting on the infinite grid of stone columns based on unit cell concept. In this concept, the soil around a stone column for area represented by a single column, depending on column spacing, is considered for the analysis. As all the columns are simultaneously loaded, it is assumed that lateral deformations in soil at the boundary of unit cell are zero. The settlement improvement factor is derived as a function of area ratio and angle of internal friction of column material. The calculation of the improvement factor was done by considering the stone columns material is incompressible and column is based on a rigid layer (end-bearing). Priebe [7] considered the effect of compressibility of the column material and the overburden. He developed design charts to calculate the settlement of single and strip footing reinforced by a limit number of stone columns. Poorooshasb and Meyerhof [8] proposed the performance ratio, which is defined as the ratio of the settlement of the improved ground to unimproved ground under identical surcharges. They considered linear elastic behavior for stone column. Balaam et al. [9] proposed a finite-element approach for soft clay treated with granular piles and reported the effect of stiffness of granular pile on load deformation behavior. Ambily and Grandhi [10] conducted experimental and numerical analysis on singles and groups of stone columns. They presented improvement factor without considering stress due to installation of stone column. Han and Ye [11] developed a simplified and closed form solution for estimating the rate of consolidation of the stone column reinforced foundations accounting for the stone column soil modular ratio. Guetif et al. [12] the installation of stone column in soft clay simulated by adopting a composite cell model. They reported that the improvement of the Young modulus of soft clay, due to the consolidation caused by the installation of the vibrocompacted column, should be considered in the design procedure.

This paper is presented in the following sequences. First, the simulation of stone column in soft soil in plain strain is introduced. Next, the simulation of the column installation in soft clay by means of vibrocompaction technique is introduced. Finally, settlement improvement factor is calculated and is compared with existing theories.

2. MODELING AND BOUNDARY CONDITIONS

Numerical model was developed using Plaxis program. Plaxis is used for the analysis of deformation and stability in geotechnical engineering. The improved Soil is modeled with 15 nodes triangular finite elements. Axisymmetrical condition was assumed for the case of stone column; whereas, plane strain condition was considered for group of stone columns. The mesh was medium generation, utilized as the global coarseness of model; whereas, it was refined in the area of reinforced ground, because stresses and displacements are higher in this area. The initial vertical stress due to gravity load has been considered in the analysis. The clay layer in this study was dry. Hence, there was no need to enter ground water condition.

Stone columns usually are extended to bedrock or a hard layer, but occasionally floating columns are also installed. Fig.1 shows the modeling of reinforced soil by a group of stone columns. Each column acts within a cylindrical cell with a radius of influence (R_e). Balaam and Booker [13] related the radius of influence to the actual column spacing by the relation $R_e = c.S$, where S is the actual spacing (from center to center of the columns) and c is a constant having values of 0.525 and 0.564 for triangular and square patterns, respectively. For most practical cases, the diameter of influence may be assumed to be equal to the actual column spacing. The analyses were carried out assuming columns were arranged in a square pattern.

In this investigation, it was assumed that the raft is rigid, and both the stone column and soft clay undergo the same amount of settlement. There are no interface elements placed between the soil and the footing, so any slippage between footing and soil occurs within the soil. This is realistic, because concrete footings poured against the ground form a very rough interface. Fixed supports were considered at the bottom of geometry and roller supports were on the vertical boundaries. At the interface between the stone column and soft clay, interface elements have been used. This can be explained by the fact that the deformation of the column is mainly by general failure and causes significant shear between clay and stone column [14].

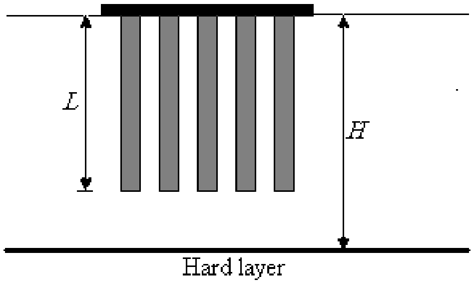

Fig.1. Modeling of reinforced soil by a group of stone columns

The arrangement of the test columns is generally 3D. For modeling column in plain strain, the use of equivalent strip is necessary. The idealization formula for the equivalent strip is given in Fig.3. The area replacement percent (ρ), total area of stone columns over area of unreinforced soil, assuming columns were arranged in a square pattern is considered as

$$\rho = \frac{d^2}{(1.13S)^2} \times 100 \tag{1}$$

The area replacement percent is considered between 10% to 30%. For the amount of less than 10%, no significant improvement in the ground properties is achieved [15]; whereas, there would be installation difficulties for the area replacement percent more than 30%. In most practical cases a soil layer is placed at the top soft clay reinforced with stone columns, so a sand layer of 20 cm thick was placed at the top of model. The diameter of the finished stone column depends on the strength and consistency of the soil, the energy of compaction and diameter of casing. In the softer soil, the diameter of the stone is increased because compaction of the aggregate pushes the stone into the surrounding soil. The analysis was carried out on stone column with the diameter of 1 m and height of 10 m. The clay layer was supposed with the depth of 10, 15 and 20 m. Because of symmetry, only half of the geometry is modeled.

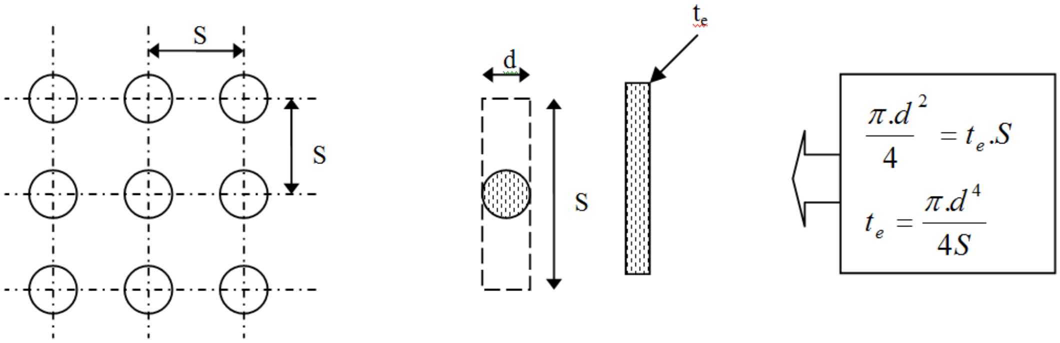

Fig.2. Idealization of stone columns in plane strain

Appropriate choices of material properties are necessary in order to have an accurate simulation of reinforcement system in the numerical modeling. The properties of soft clay, stone column and sand were found in the literature [10, 12 and 16]. Axisymmetric and plain strain analyses were carried out with considering elasto-plastic behavior for soft clay, sand and stones. A drained behavior is assumed for all the materials. In this investigation, the constitutive law of Mohr coulomb was used for the stone columns, sand and soft soil. The input parameters of Mohr Coulomb model (E, μ, φ◌́, ψ, c◌́, and γ) are given in Table 1. Before the columns are installed, the horizontal component of stress in the ground is given by the equation $k_0\gamma z$, where z is the depth below ground surface and k_0 is the coefficient of the rest earth pressure for the soft clay. The coefficient of earth pressure at rest value was estimated from the Jacky's formula:

$$k_0 = 1 - \sin\varphi \tag{2}$$

Installation of the columns increases this stress to a higher value. Suitable value for interface strength (R_{inter}) between stone column and soft clay was found in the literature [17].

Table 1. Parameters used in the numerical analysis

	E(Kpa)	*v*	*φ(°)*	*ψ(°)*	*c(Kpa)*	*γ (kN/m²)*	*R_{inter}*
Soft clay	4000	0.35	23	0	0	15	0.7
Stone column	55000	0.3	43	10	0	19	0.9
sand	20000	0.3	30	4	0	16	-

3. ANALYSIS AND DISCUSSION

The installation of stone column is accompanied by vibration and horizontal displacement of soil. The lateral expansion generates large strains about of 45 percent in soft clay next to the column. So, surrounding soft soil is compressed and increase coefficient of lateral earth pressure. The value of coefficient of lateral earth pressure after the installation of stone column depends largely on the type of soil, spacing of stone columns and installation method of stone column. For determination of the stress values due to column installation, an axisymmetric study was carried out. Vibratory probes are typically utilized to construct a stone column, the probe itself generally consisting of a 12 to 16 inch diameter hollow cylindrical body. In Fig.3, the installation of stone column in soft clay has been simulated. At first, in modeling the cylindrical hole occupied by the vibroprobe with radius of 0.25 m (which is a typical value with the wet-top-feed technique). Then, along the border of cylindrical hole the soft clay is subjected to radial displacement that simulates the vibrocompaction installation until the horizontal expansion reaches the column radius of 0.5m. At the mid-thickness of soft soil layer is drew a line for determination of stresses.

Fig.4 shows the variation of stresses in soft soil with distance from column after installation of column. After the expansion of the column a new distribution of stresses takes place in the surrounding soft clay that can be quantified by the ratio between effective horizontal and vertical stresses (σ_h/σ_v). Variation of stress in soft soil after installation of column with distance from column is significantly reduced. Consequently the coefficient of lateral earth pressure at rest, denoted by K_0, increases from its initial value ($K_0 = 1 - \sin\varphi = 0.609$) in soft clay to values exceeding one at the vicinity of the column. It should be considered that since the soil is compressed from both sides, the magnitude of increase in soil pressure would be twice as much as the pressure that is calculated from Fig.4.

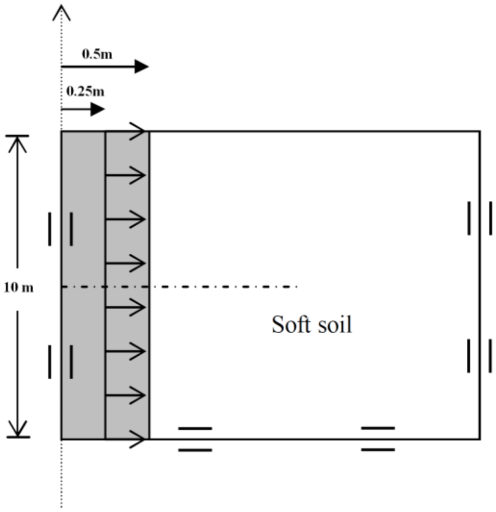

Fig.3 Simulation of installation of stone column in soft clay

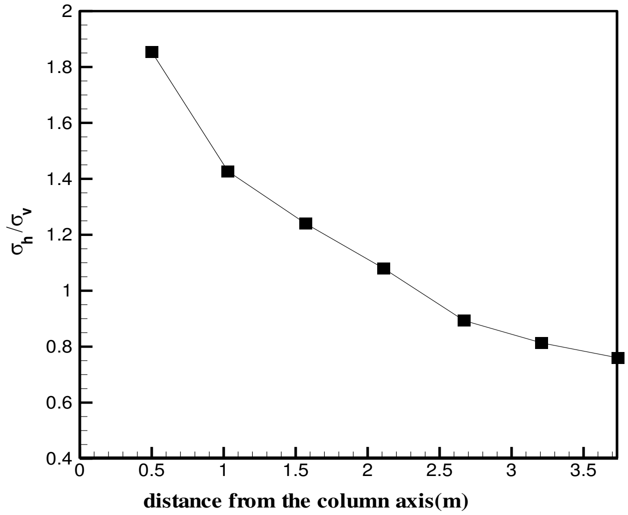

Fig.4. Variation of stresses in soft clay with distance from the column

In this analysis, the improvement of the stiffness (reduction of settlement) of the treated ground was evaluated. Improvement of a soft soil by stone columns is due to three factors. The first factor is inclusion of a stiffer column material (such as crushed stones, gravel, and so alike. . .) in the soft soil. The second factor is the densification of the surrounding soft soil during the installation of stone column. The third factor is the acting as vertical drains [12]. So, the insertion of stone columns into weak soils is not just a replacement operation and stone column can changes both the material properties and the state of stresses in the treated soil mass. In this analysis, the effect of stiffness of column material and the densification of the surrounding soft soil during the installation of stone column were considered. For considering horizontal component of stress due to installation of the columns, Fig.4 was used.

Fig.9 shows a model of group of stone columns in finite-element analysis when entire area is loaded. A uniform vertical displacement was prescribed to the model. The average settlement (S_e) can be calculated by the following equation [18]:

$$S_e = \mu_0 . \mu_1 . \frac{q.B}{E} \tag{3}$$

Where q is the applied footing load, E is elastic Modulus of the soil, μ_0 and μ_1 values depend on the depth of the footing and the thickness between the footing base and hard strata, respectively. Therefore, settlement is depending on elastic modulus of the soil. Assuming the whole soil medium to be homogeneous, the equivalent secant modulus values (E_{eq}) have been calculated as

$$E_{eq} = \frac{\sigma}{\varepsilon} \tag{4}$$

Where

$$\varepsilon = \frac{S}{L} \tag{5}$$

Where, σ is the average applied stress, ε is the average strain, S is the settlement of the footing and L is the depth of the clay bed (=10 m). Fig.5 shows typical axial stress versus settlement behavior for improved ground based on finite-element analysis at different area replacement percent. The vertical stress versus settlement relation is almost linear. The equivalent Young's modulus of the composite ground can be obtained from average slope of the plot. Settlement reduction ratio (*SRR*), settlement of the composite ground divided by settlement of ground without stone column at the same stress level, was calculated. Using Eq.3, *SRR* can be expressed as

$$SRR = \frac{E_0}{E_{eq}} \tag{6}$$

Where, E_0 is Young's modulus of ground without stone column.

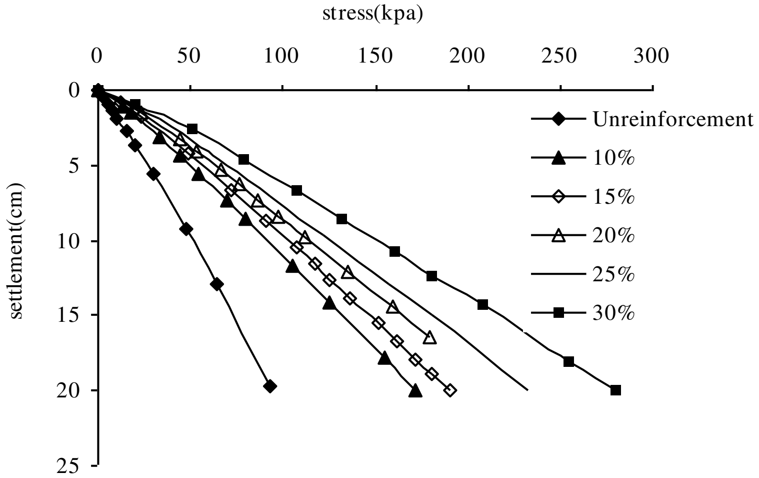

Fig.5. Stress settlement behavior under loading

Fig.6 shows the effect of the strain level on the computed *SRR* values. Effect of the strain on the *SRR* is small. This is mainly due to vertical stress versus settlement relation is almost linear. The strain level effects on the *SRR* in high area replacement percent. Considering the fact that the magnitude of increase in stiffness of stone column and soft clay are different, SRR changes due to increase of strain level.

Fig.7 shows the effect of *H/L* on the computed SRR values. With increase of *H/L*, value of *SRR* is increased. With increase of *ρ*, effect of *H/L* on the computed *SRR* is increased. The settlement of stone column foundations consists of two components; the settlement contributed by the soil treated by stone columns and the settlement contributed by the soil below the stone columns. In high area replacement percent (*ρ=30 %*), effect of *H/L* on the computed *SRR* is small. It shows in high area replacement percent the settlement contributed by the soil below the stone columns is small. So, floating stone columns in high area replacement percent, because of used frictional material significantly reduce the settlement. In low area replacement percent (*ρ=10 %*), effect of *H/L* on the computed *SRR* isn't small and the significant reduction doesn't occur in settlement.

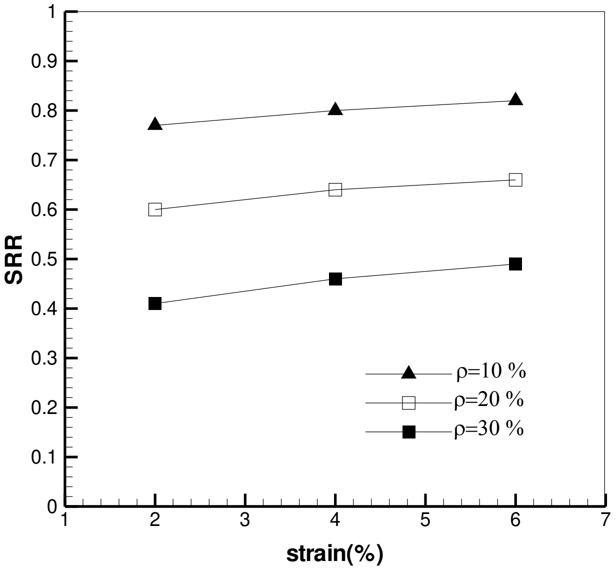

Fig.6 Effect of the strain level on *SRR*

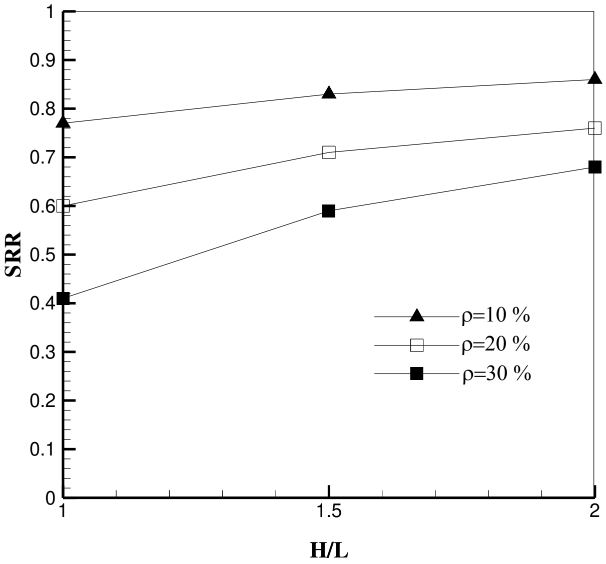

Fig.7 Effect of *H/L* on SRR

In order to judge the results of the numerical analysis a comparison is made with the results of standard analytical design methods. Table 2 shows *SRR* obtained from the present work for different area ratio. Results were compared with the existing theories. Poorooshasb et al [12] and Priebe [3, 11] supposed that stone columns are extended to bedrock or a hard layer. The present work predicts an upper *SRR* compared to Poorooshasb et al [12] and Priebe [3, 11]. Poorooshasb et.al considered only elastic displacement, whereas in the present work was also considered plastic displacement, predicts upper settlement compared to Poorooshasb's method.

Priebe [3] was done the calculation of the basic improvement factor (*SRR*) by considering the stone columns material is incompressible. Furthermore assumed that the column is based on a rigid layer (end-bearing) and the unit weights of column and initial soil are neglected Therefore, this suppositions are caused the settlement is decreased. However, column material is compressible and stone column may be floating. Beside, for uncompressible material, in the case where the area replacement percent to $\rho=100\%$, the *SRR* achieve to zero. In present work, in the case where the area replacement percent to $\rho=100\%$, the *SRR* achieve to 0.09(Young's modulus of soft soil divided by Young's modulus of stone column). The actual *SRR* does not achieve to zero. Therefore, the values of *SRR* obtained from present work are close to actual *SRR*.

Table 2. Comparison of *SRR* with existing theories

ρ	Present work			Priebe(1976)	Priebe(1995)	Poorooshasb et
	H/L=1	*H/L=1.5*	*H/L=2*	*(H/L=1)*	*H/L=1*	al(1996)(*H/L=1)*
10	0.77	0.83	0.86	0.61	0.62	0.65
15	0.67	0.76	0.83	0.50	0.52	0.52
20	0.60	0.71	0.76	0.42	0.44	0.43
25	0.50	0.63	0.69	0.35	0.38	0.35
30	0.41	0.59	0.68	0.29	0.33	0.28

4. CONCLUSIONS

A series of numerical analysis has been carried out to evaluate compaction and settlement of soil reinforced by a group of stone columns. The clay layer was assumed to be uniform. The analyses employed an elastic–perfectly plastic constitutive model following the Mohr–Coulomb failure criterion. Based on the results of this numerical study, we can draw the following conclusions:

1. Variation of stress in soft soil after installation of column with distance from column is significantly reduced.

2. The load settlement behavior of model with an entire area loaded is almost linear and it is possible to find the stiffness of improved ground.

3. Effect of the strain on the *SRR* is small due to vertical stress versus settlement relation is almost linear.

4. Floating stone columns in high area replacement percent, because of used frictional material significantly reduce the settlement.

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