

Settlement evaluation of soft clay reinforced with stone columns using the equivalent secant modulus

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Abstract A method is proposed to evaluate settlement of soft clay reinforced with stone columns. Finite element analyses were carried out using 15-noded triangular elements with *PLAXIS*. A drained analysis was carried out using Mohr–Coulomb’s criterion for soft clay, stones, and sand. The stress due to column installation has been considered in the analysis. At the interface between the stone column and soft clay, interface elements have been used. The settlement ratio (SR) of the soil has been estimated using the equivalent secant modulus. The results are compared with those available in the literature, and the advantages of the numerical analysis were highlighted. Based on the results of this analysis, the SR decrease with compaction surrounding soft soil, but decrease of SR is mainly due to a stiffer column material in soft clay.

Keywords Settlement ratio · Stone columns · Finite element method · Area replacement percent · Equivalent secant modulus

Introduction

Man does not have any control on the process of soil formation. 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 loads. In such cases, the properties of the soil within the

zone of influence have to be improved in order to make them suitable to support the given loads. Ground improvement for the purpose of foundation construction essentially means increasing the shear strength of the soil and reducing the compressibility to a desired extent. A number of techniques have been developed in the last 50 years. Stone columns are extensively used to improve bearing capacity of poor ground and reduce settlements of structures built on them. The techniques were first employed in Europe in the 1830s and have been used there extensively since the late 1950s (Ambily and Grandhi 2007).

The mechanics of ground improvement depend largely on the type of soil. Cohesive soils can be improved using stone columns. Stone columns may also be used in sand deposits but have particular application in soft, inorganic, cohesive soils. The construction of stone columns is generally carried out using either a replacement or a displacement method. In the replacement or wet method, native soil is replaced by stone columns in a regular pattern where the holes are constructed using a vibratory probe accompanied by a water jet. In the displacement or dry method, native soil is displaced laterally by a vibratory probe using compressed air. When the probe is reached to favorite depth, the stones are added and are compacted by the vibrating probe. The displacement method is appropriate where ground water level is low and in situ soil is firm (Lee and Pande 1998). The installation of stone column is accompanied by vibration and horizontal displacement of soil. For considering horizontal displacement of soil during the installation of stone column, many researchers considered coefficient of lateral earth pressure (K^*) bigger than the coefficient of lateral earth pressure at rest (K_0) (Priebe 1976; Elshazly et al. 2006; Elkasabgy 2005; Pitt et al. 2003). Elshazly et al. (2007) presented an interesting relation between the inter-column spacing and K^* in

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vibro-installation technique (Fig. 1). This relation was inferred from analyses for load settlement records of various field load tests, performed for stone column arrangements with different inter-column spacing values. A well-documented case history, involving three-column patterns (group of columns with three different spacing) 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 researchers have developed theoretical solutions for estimating bearing capacity and settlement of foundations improved by stone columns (Greenwood 1970; Hughes et al. 1976; Aboshi et al. 1979). Priebe (1976) 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 to be incompressible and column is founded a rigid layer (end-bearing). Priebe (1995) 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 limited number of stone

columns. Poorooshasb and Meyerhof (1996) proposed the performance ratio, which is defined as the ratio of the settlement of the improved ground to that of the unimproved ground under identical surcharges. They considered linear elastic behavior for stone column. Balaam et al. (1978) 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. Mitchell and Huber (1985) compared the field performance of stone columns by an axisymmetric finite element model with groups of columns surrounding the central column replaced by a ring of stone material having equivalent thickness. Ambily and Grandhi (2007) conducted experimental and numerical analysis on singles and groups of stone columns. They presented improvement factor without considering stress due to installation of stone columns.

Field observations showed that stone columns could also accelerate the rate of consolidation of soft clays (Han and Ye 1992). Han and Ye (2001) 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. It is also reported in the paper that during the process of consolidation the stress on stone column increases with time, whereas the stress on soil decreases. At the end of consolidation, a steady stress concentration ratio is approached.

This paper is presented in the following sequences. First, the simulation of stone column in soft soil in plain strain is introduced. Next, settlement improvement factor is calculated using the equivalent Young's modulus. Finally, results are compared with existing theories.

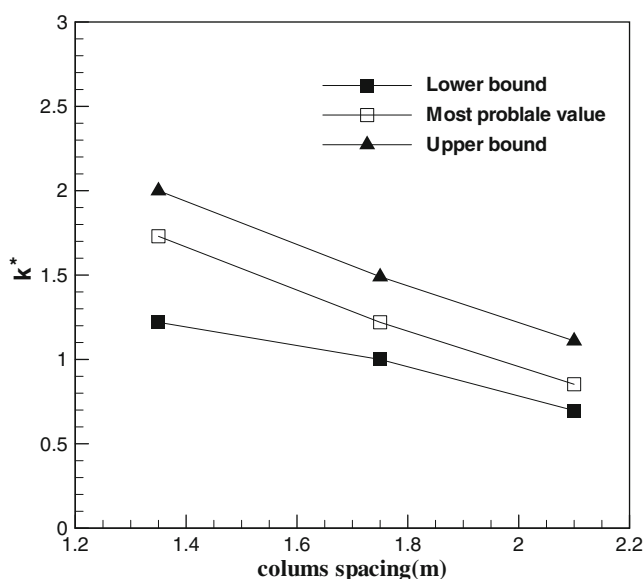


Fig. 1 Variation of K^* with columns spacing (Elshazly et al. 2007)

Finite element analysis

Numerical modeling was performed using the *PLAXIS* V8 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. In the area of reinforced ground, because stresses and displacements are higher in this area, the considered medium mesh size was refined.

Geometric modeling

Each column acts within a cylindrical cell with a radius of influence denoted by R_c (Fig. 2). Balaam and Booker (1981) related the radius of influence to the actual column spacing by the relation $R_c = c \cdot S$, 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

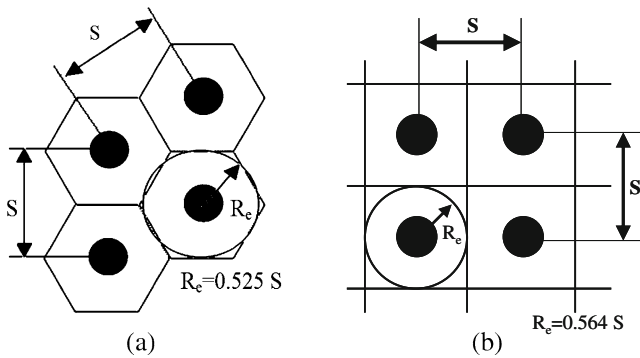


Fig. 2 Plan of stone column **a** triangular pattern and **b** square pattern

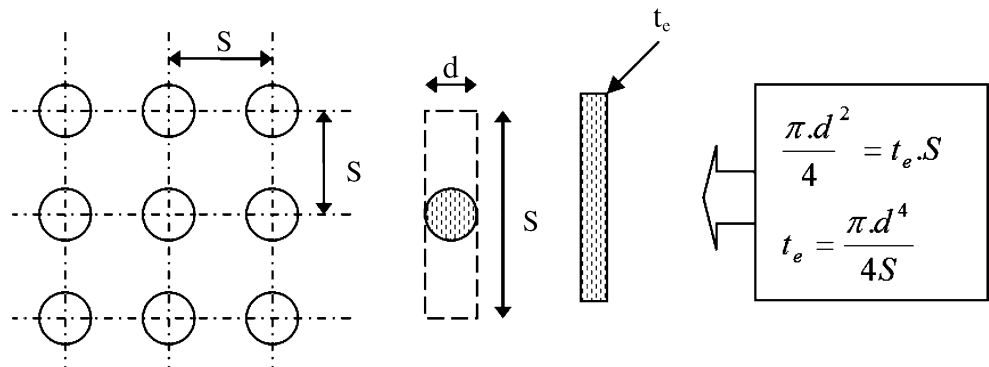
equal to the actual column spacing. The analyses were carried out assuming columns were arranged in a square pattern.

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 which produces significant shear between clay and stone column (Etezad 2006).

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 original area of unreinforced soil, assuming columns were arranged in a square pattern was considered as:

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

Fig. 3 Idealization of stone columns in plane strain



The area replacement percent is considered between 10% and 30%. For values less than 10%, no significant improvement in the ground properties is achieved (Hu et al. 1977); whereas, there would be installation difficulties for the area replacement percent more than 30%. Stone columns usually are extended to bedrock or a hard layer, but occasionally floating columns are also installed. In this investigation, it is supposed that stone columns are extended to a hard layer. 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 such layer. The analysis was carried out on stone column with the diameter of 0.8, 1.0, and 1.2 m and depth of 10 m. Because of symmetry, only half of the geometry is modeled.

Material modeling

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 can be found in the literature (Ambily and Grandhi 2007; Guetif et al. 2007). Plain strain analyses were carried out considering elastoplastic 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 ($E, \mu, \phi, \psi, c,$ 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 lateral earth pressure at rest value was estimated from the Jacky’s formula:

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

Installation of the columns increases this stress to a higher value. Horizontal component of stress due to installation of the columns, the coefficient of the rest earth

Table 1 Parameters used in the numerical analysis

	E (Kpa)	ν	ϕ (°)	ψ (°)	c (Kpa)	γ (kN/m ²)	R_{inter}
Soft clay	4,000	0.35	21	0	5	17	0.7
Stone column	55,000	0.3	43	10	0	19	0.9
Sand	20,000	0.3	30	4	0	16	-

pressure increased. In *PLAXIS*, the material properties of interface are related to the soil properties and are entered in the same data sets as the soil properties. For interaction between stone column and soft clay, the interface is weaker than the soil layer, which means that interface strength (R_{inter}) should be less than 1. Suitable value for interface strength (R_{inter}) between stone column and soft clay was found in the literature (Brinkgreve and Vermeer 1998).

Analysis

The initial vertical stress due to gravity load has been considered in the analysis. The stress caused by column installation depends on the method of construction and type of soil. In this investigation for considering the stress due to column installation, initial horizontal stress (K_0) is increased. Groundwater was supposed to be more than 10 m below the ground surface. Hence, there was no need to enter groundwater condition.

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 on...) in the soft soil. The second factor is the densification

of the soft soil surrounding the stone columns during the installation of stone column. The third factor is the vertical drainage provided by stone columns (Guetif et al. 2007). Therefore, the insertion of stone columns into weak soils is not just a replacement operation and stone column can change 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.

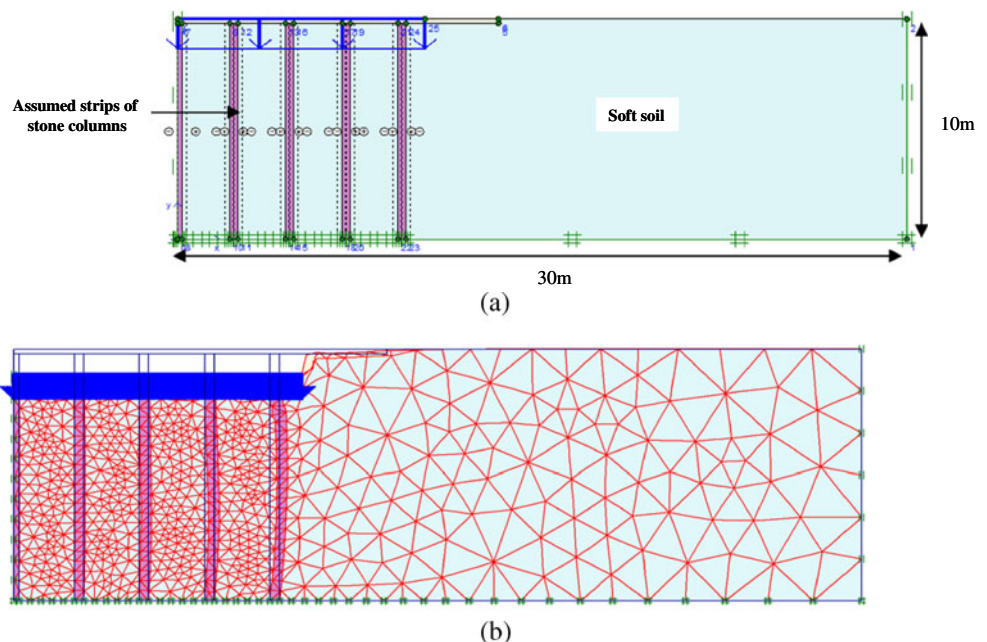
Figure 4 shows a model of group of stone columns in finite element analysis when entire area is loaded. A uniform vertical displacement ($\varepsilon=2\%$) was prescribed to the model. The average settlement (S_e) can be calculated by the following equation (Christian and Carrier 1978):

$$S_e = \mu_0 \cdot \mu_1 \cdot \frac{q \cdot B}{E} \quad (3)$$

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

$$E_{eq} = \frac{\sigma}{\varepsilon} \quad (4)$$

Fig. 4 Simulation of reinforcement system in the numerical analysis **a** initial model and **b** deformed mesh



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 thickness of the clay bed (=10 m). Figure 5 shows typical axial stress versus settlement behavior for improved ground based on finite element analysis at different area replacement percentage. 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 ratio (SR), settlement of the composite ground divided by settlement of ground without stone column at the same stress level, was calculated. Using Eq. 3, SR can be expressed as

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

where, E_0 is Young’s modulus of ground without stone column.

The installation of stone column is accompanied by vibration and horizontal displacement of soil. The lateral expansion generates large strains approximately 45% in soft clay next to the column. The surrounding soft soil is compressed and coefficient of lateral earth pressure increase. 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. Figure 6 shows the value of SR for four different values of $K^*=(k_0, 1.25k_0, 1.50k_0, 1.75k_0)$. The average of SR of various diameters was calculated as

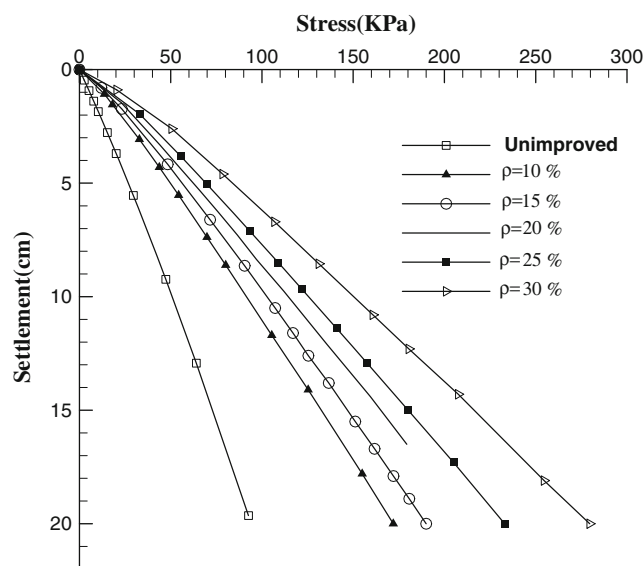


Fig. 5 Stress settlement behavior under loading for different area replacement percent (finite element results)

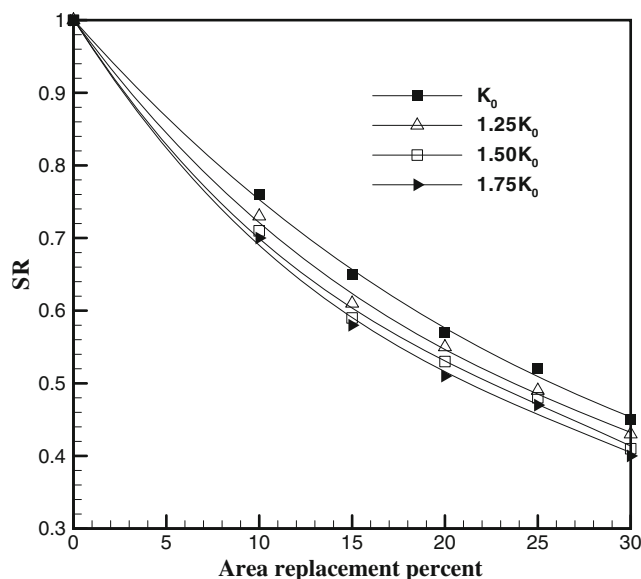


Fig. 6 Effect of soil compaction on SR

SR for each area replacement percent. Use of k_0 means that the installation of stone column does not have effect on the surrounding soft soil. Figure 6 shows that stone column improves the ground mainly due to the higher stiffness of the columns compared to the soil. In other words, stone column decreases largely settlement even if the insertion of stone columns into weak soils be considered just a replacement operation without any effect on surrounding soft soil.

An increase of 25% in k_0 resulted in a decrease of about 4% of SR. Therefore, decrease of SR is not only due to stiffer column material soft clay but SR decreases with compaction of surrounding soft soil. With increase of K^* , value of SR is decreased. The value of coefficient of lateral earth pressure after the installation of stone column depends largely on spacing of stone columns. Elshazly et al. (Mitchell and Huber 1985) presented the interesting relation between the spacing of stone columns and K^* in vibro-installation technique. For considering horizontal component of stress due to installation of the columns, Fig. 1 was used.

The diameter of the finished stone column depends on the strength and consistency of the soil, the energy of compaction, and diameter of probe in replacement or displacement method. In the softer soil, the diameter of the column is increased because compaction of the aggregate pushes the stone into the surrounding soil. Figure 7 shows effect of diameter of column on SR. In general, the SR increases with increase in the diameter of column. With increase of area replacement percent, the effect of diameter of column on SR increases. This can be explained by the fact that in small diameters, column spacing decreases and consequently, surrounding soft soil is compacted properly.

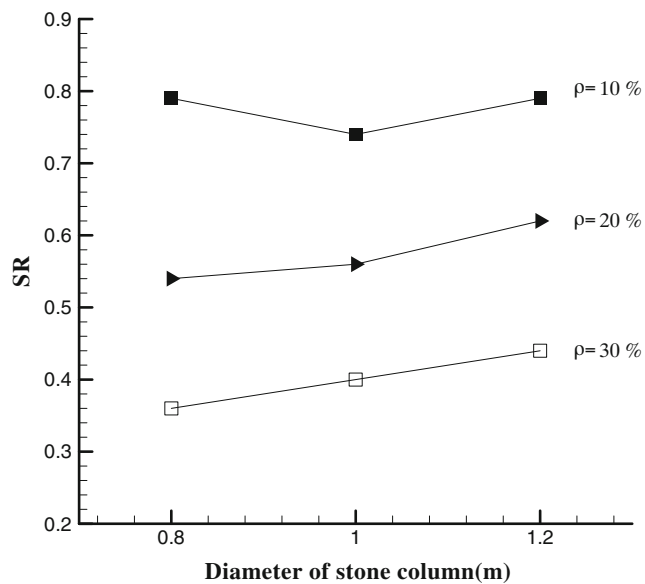


Fig. 7 Effect of diameter of column on SR

In order to judge the results of the numerical analysis, a comparison is made with the results of standard analytical design methods. Figure 8 shows SR obtained from the present work for different area ratio. The following relationship is obtained between SR and replacement area:

$$SR = 2.78\rho^2 - 2.86\rho + 1 \quad (7)$$

Results were compared with the existing theories. The present work predicts an upper SR compared to Poorooshasb et al. (Poorooshasb and Meyerhof 1996) and Priebe (1976; 1995). Poorooshasb et. al considered only elastic displace-

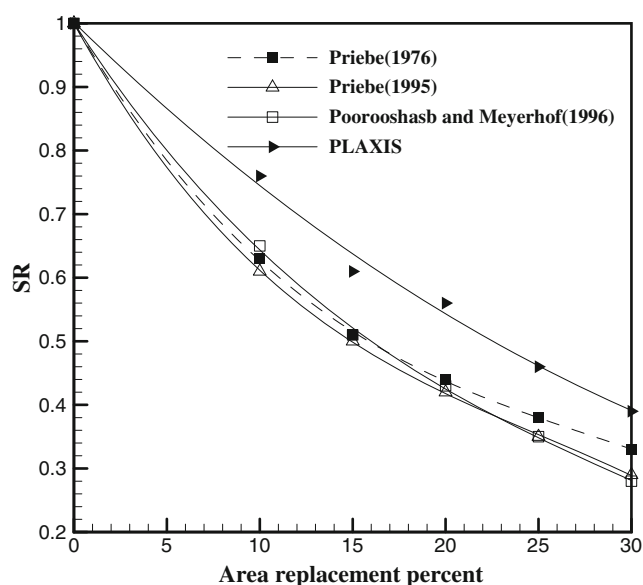


Fig. 8 Comparison of SR with existing theories

ment, whereas in the present work both elastic and plastic displacement is considered. Therefore the present work predicts higher settlement compared to Poorooshasb's method.

Priebe (1976) performed the calculation of the basic improvement factor (SR) by considering the stone columns material to be incompressible. Therefore, any settlement of the load area results in a bulging of the column which remains constant all over its length. However, column material is compressible, and failure of stone column is in the form of shear failure (Etezad 2006). Therefore, calculated settlement in the present work will be more than Priebe's method. Besides, for incompressible material, in the case where the area replacement percent increases up to 100%, the SR approaches to zero. But in the present work, with increase of area replacement percent up to 100%, the SR decreases to 0.09 (Young's modulus of soft soil divided by Young's modulus of stone column). The actual SR does not achieve to zero. Therefore, the values of SR obtained from present work are close to actual SR.

Example

Using the results of the present analysis, settlement of a circular foundation with the diameter of 10 m is calculated. This foundation is placed on clay layer of 10-m thick and imposes vertical stress of 100 kPa. The average properties of soft clay are: cohesion=5 kPa, angle of internal friction=21° and modulus of elasticity=4,000 kPa. The stones used for columns have modulus of elasticity=55,000 kPa and angle of internal friction=43°. Soil is improved using 100 cm diameter stone column with spacing of 200 cm center to center. The settlement of untreated ground using Eq. 3 is 75 mm. Using Eq. 7 and for $\rho=0.2$, SR is calculated as 0.54. So, settlement of foundation after treatment = $0.54 \times 75 = 40.5$ mm.

Conclusions

A series of numerical analysis has been carried out to evaluate 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, the following conclusions can be drawn:

1. 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.

2. The SR decrease with compaction surrounding soft soil, but decrease of SR is mainly due to a stiffer column material in soft clay.
3. The SR values depend mainly on column spacing (area replacement percent).
4. In the certain area replacement percent, decrease in diameter of column decreases the value of SR, and this decrease is because of reduction of columns spacing. Increase in area replacement percent results in increase in the effect of diameter of column on SR.

References

- Aboshi H, Ichimoto E, Harada K, Emoki M (1979) The composer—a method to improve the characteristics of soft clays by inclusion of large diameter sand columns. Proc., Int. Conf. on Soil Reinforcement., E.N.P.C., 1, Paris 211–216
- Ambily AP, Grandhi SR (2007) Behavior of stone columns based on experimental and FEM analysis. J Geotech Geoenviron Eng ASCE 133(4):405–415
- Balaam NP, Booker JR (1981) Analysis of rigid rafts supported by granular piles. Int J Num Anal Methods Geomech 5:379–403
- Balaam NP, Poulos HG, Brown PT (1978) Settlement analysis of soft clays reinforced with granular piles. Proc., 5th Asian Conf. on Soil Engineering, Bangkok, Thailand, 81–92
- Brinkgreve RB, Vermeer PA (1998) Plaxis-finite element code for soil and rocks analysis. Version 8.2 Rotterdam Brookfield, AA. Balkema
- Christian JT, Carrier WD (1978) Janbu, Bjerrum and Kjaernsli's chart reinterpreted. Canadian Geotechnical Journal 15:123–128
- Elkasabgy MA (2005) Performance of stone columns reinforced grounds. M.Sc. Thesis, Zagazig University, Faculty of Engineering at Shobra, Cairo
- Elshazly HA, Hafez D, Mosaad M (2006) Back calculating vibro-installation stresses in stone columns reinforced grounds. J Ground Improve 10(2):47–53
- Elshazly H, Elkasabgy M, Elleboudy A (2007) Effect of inter-column spacing on soil stresses due to vibro-installed stone columns: interesting findings. Geotech Geol Eng (2008) 26:225–236
- Etehad M (2006) Geotechnical Performance of Group of Stone Columns. Ph.D. Thesis, University of Montreal Quebec
- Greenwood DA (1970) Mechanical improvement of soils below ground surfaces. Proc., Ground Engineering Conf., Institution of Civil Engineers, London, 11–22
- Guétif Z, Bouassida M, Debats JM (2007) Improved soft clay characteristics due to stone column installation. Comput Geotech 34(2007):104–111
- Han J, Ye SL (1992) Settlement analysis of buildings on the soft clays stabilized by stone columns, Proc., Int. Conf. on Soil Improvement and Pile Found., 118, 446–451
- Han J, Ye SL (2001) Simplified method for consolidation rate of stone column reinforced foundation. J Geotech Geoenviron Eng 127(7):597–603
- Hu W, Wood D M, Stewart W (1977) Ground improvement using stone column foundation: results of model tests. Proc., Int. Conf. on Ground Improvement Techniques, Macau, 247–256
- Hughes JMO, Withers NJ, Greenwood DA (1976) A field trial of reinforcing effect of stone column in soil. Proc., Ground Treatment by Deep Compaction, Institution of Civil Engineers, London, 32–44
- Lee JS, Pande GN (1998) Analysis of stone column reinforced foundations. Int J Numer Anal Meth Geomech 22:1001–1020
- Mitchell JK, Huber TR (1985) Performance of a stone column foundation. J Geotech Engrg 111(2):205–223
- Pitt J M, White DJ, Gaul A, Hoevelkamp K (2003) Highway applications for rammed aggregate piers in Iowa soils, Iowa DOT Project TR-443, CTRE Project 00-60, USA.
- Poorooshasb HB, Meyerhof GG (1996) Analysis of behavior of stone columns and lime columns. Comput Geotech 20(1):47–70
- Priebe HJ (1976) Abschätzung des setzungsverhaltens eiens durch stopfverdichtung verbesserten baugrundes. Die Bautechnik 54:160–162 (in german)
- Priebe HJ (1995) The design of vibro replacement. Ground engineering 28:31–37