The 3D numerical model of the stone column in soft clay soils

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Abstract. An end bearing stone column is one of the most common types of stone columns, which completely penetrates through a layer of soft clay soils, resting on much stiffer soils. This article presents a numerical model (analyses) of the stone column used to strengthen the soft clay soil. The analyses were performed using a three-dimensional model in FLAC3D. To investigate the effect of the stone column on strengthening soft clay soils, a dimensionless parameter called the settlement improvement ratio (Ks) is used. The results show that, the settlement improvement ratio (Ks) increases with an increasing diameter of the stone column. The lateral deformation of the stone column decreases with the increasing stone column diameter, and the maximum lateral deformation was occurred at approximately (1.0 to 1.5) diameter from the top of the surface.

1. Introduction

In recent times, the population increase results in using all the areas, especially those that contain soft clay soils. Therefore, there was a necessity to improve the soft clay soil to reduce their value of compression. There are many types of the soil improvement techniques and one of those techniques is known as the stone columns. Stone columns are a cost-effective and environmentally friendly technique improving the soft clay soils. Their usage effectively increases the load-bearing capacity and reduces the foundation settlement, accelerates the dispersion of the excess pore water pressure due to their high relative permeability, as well as shortens the drainage path, well-graded clean sand or gravel are common materials for such columns.

Many works of scientists and specialists are conducted to study the behavior of the stone column on soft clay soils. The stone columns provide significantly improvements of the soft soil behavior. Some of them suggested methods of calculating the bearing capacity (Hughes et al. (1975) [1]; Bouassida et al. (1995) [2]; Etezad et al. (2014) [3]), and others presented a prediction model to calculate the settlement of the soil reinforced by the stone columns (Prieb (1995) [4]; Balaam and Booker (1981) [5]; Castro (2016) [6]). Furthermore, to investigate the effect of the geometry conditions and physical properties, which affect the behavior of the improving process, field, laboratory and numerical tests were performed (Ambily and Gandhi (2007) [7]; Elshazly et al. (2008) [8]; Usmanov (2008) [9]; Bay et al. (2009) [10]; Elsawy et al. (2009) [11]; Shahu and Reddy (2011) [12]; Piskotin et al. (2016) [13]; Killeen and McCabe (2014) [14]; Stavnitser et al. (2014) [15]; Sexton et al. (2014) [16]; Basack et al. (2018) [17]; Znamenskii and Sayed (2019) [18]; Ter-Martirosyan et al. (2019) [19]).
The main purpose of this work was to continue researching the influence of the stone columns on the improvement and reduction of the footing settlement on the soft clay soil and the dependence of this influence on the diameter of the columns. In addition, the shape of the lateral deformations of the stone columns depending on their diameter is considered.

2. Numerical modelling

2.1. Model details

The analysis was carried out using the three-dimensional finite-difference numerical model FLAC3D. A three-dimensional quarter of the axisymmetric scale model consisted of the soft soil, stone column and footing (figure 1b). A model was developed to simulate the time-dependent behavior of the stone column–improved soft soil under the applied load on a footing where simultaneous activities occur in the form of the fluid flow and change in mechanical properties of the improved soil. The excess pore pressure starts to dissipate in the form of the fluid flow because of the gravity loading, which causes the consolidation of the soft soil (Itasca (2006) [20]; Pham and White (2007) [21]; Castro (2017) [22]; Das and Deb (2018) [23]).

The soft soil was modelled by an elastic-plastic model based on the Mohr-Coulomb failure criterion in the FLAC3D software. The parameters of the mechanical characteristics of the weak soils are given in table 1. It is considered that the soft soil has an anisotropic coefficient of permeability. The ratio of the coefficient of permeability in the radial direction (k_r) to the coefficient of permeability in the vertical direction (k_z) is assumed to be 3. The thickness of the soil layer (H) was assumed to be 10 m. Ground water is located on the surface of the clay layer. The width and length of the soil model are assumed to be ≥ 10 B, where the B is width of the footing.

The model consisted of four stone columns with a diameter (d) = 0.8, 1.0 and 1.2 m, a length (L) = 10 m, with a distance between their centers of 2.0 m. The stone column was modeled as a conventional elastic-plastic model based on the Mohr-Coulomb failure criterion in the FLAC3D software. The footing with a width of B = 4 m and a height of 0.7 m was modeled as rigid. The footing was loaded with a uniformly distributed load (P) equal to 50, 100 and 150 kPa.

The initial condition was assumed to be at the end of the cavity drilling. The initial stresses were obtained using the lateral soil pressure coefficient k_0, which was defined as the ratio of horizontal stresses in situ to vertical effective stresses. For a weak clay soil, k_0 = 0.7. For a stone column, k_0 = 1 - sin (φ'). The interface element was attached between along the footing soil to reflect a realistic contact condition between the footing, the soil and columns. The physical and mechanical characteristics of the model materials are shown in table 1. Also, figure 1 shows the model details and dominations.

| parameter | γ (kN/m³) | Poisson's Ratio, ν | Elastic Modulus (kPa) | Angle of friction φ’ (°) | Cohesion c’ (kPa) | Radial permeability k_r (m/s) | Vertical permeability k_v (m/s) |
|-----------|---------|-----------------|----------------------|----------------------|-----------------|--------------------------|--------------------------|
| Clay soil | 18      | 0.3             | 3000                 | 25                   | 0.1             | 3 x 10^8                  | 1 x 10^8                  |
| Stone column | 18      | 0.3             | 30000                | 40                   | 0.1             | 3 x 10^5                  | 1 x 10^5                  |
| Footing   | 25      | 0.2             | 2.5 x 10^7          | ---                  | ---             | ---                      | ---                      |

Table 1. Physical and mechanical material properties after (Tan et al. (2014) [24])
2.2. Numerical model verification

Figure 2 gives the comparison between the FLAC3D model and Tan et al (2008) [25]. The soil and the column are modelled as a linear isotropic elastic model. The same figure 2 shows the results of the analytical solution of this problem (Balaam and Booker (1981) [5]; Han and Ye (2001) [26]), and figure 3 shows the response of the elastic – plastic model. The results show that there is a good agreement between the results of the reference model Tan et al (2008) [25] and the results obtained using the FLAC3D, which can be used for further extensive studies of the work of footing on soft clay soils reinforced with stone columns.

Figure 2. Settlement vs time (elastic model).
3. Results and Discussions

3.1. Settlement improvement ratio ($K_s$)
The main objective of this section is to study the influence of the end bearing stone columns on the settlement of the soft clay soil at the base of the footing. Calculations are performed with different values of the diameter of the stone columns ($d$) at different uniformly distributed loads on the footing ($P$). To assess the effectiveness of the stone columns to reduce the settlement of the footing on the soft clay soils used the dimensionless parameter called the settlement improvement ratio ($K_s$), that was defined as the ratio of the settlement of the footing on the soft clay soil without the stone columns, to settle the same footing with the stone columns.

Figure 4 shows the relationship between the settlement improvement ratio ($K_s$) and the load value ($p$) for different stone column diameters ($d$). According to these graphs, the settlement improvement ratio ($K_s$), as expected, increases with increasing the column diameter ($d$), while this increase is negligible up to a load ($p$) of $\approx 75$ kPa, and then increases sharply and at a load ($p$) = 150 kPa can reach 5, 6 times, depending on the column diameter.
3.2. Lateral deformation

The change in the lateral deformation of a stone column with a depth (Z) at its diameters (d) = 0.80, 1.00 and 1.20 m and foundation loads (p) = 50, 100 and 150 kPa is shown in figure 5. The figure shows that the lateral deformation decreases with an increase in the column diameter and the load on the footing. The shape of the lateral deformation of the column has an irregular shape. The deformation of the column nonlinearity increases from a very small value at the top of the stone column to a peak value, which is located approximately at a depth of (1.0 – 1.5) d from the surface of the soil, and then sharply decreases to negligible values at a depth equal to (1.00 – 1.25) B.

The information obtained on the lateral deformation stone columns may be of interest from the point of view of its use in a further study of the interaction of groups of the stone columns at the base of the foundations, as well as understanding the mechanism of their failure.

![Figure 5. Change in the lateral deformation of the stone column with depth.](image)

3.3. Influence of the stone columns on the vertical displacements of the soil with depth

Figure 6 shows graphs of the distribution of the normalized vertical displacement (∆v/B) with the depth of the soil reinforced with the stone columns, for different column diameters (d) and loads on the footing (p). The graphs show that the stone columns reduce soil deformations, while the trend of changes in the soil displacement with depth, regardless of the column diameter and load intensity, remains approximately the same. In the upper part, the soil deformations are intensive and non-linearly reduced to a depth of about 4.0 m. Also, at this part, there is a significant dependence of the vertical displacements of the soil on the load (p). Then (in the lower part), the rate of the reduction in the soil settlement decreases gradually and almost linearly with an increasing depth, and the dependence on the diameter of the stone column is almost close.
4. Conclusion

- There is a good agreement between the reference model of Tan et al (2008) [25] results and the obtained results from FLAC3D software, this model may be having a significant effect on the coming future research to predict the behavior of the stone column on the soft clay soil.
- Numerical analyses have confirmed a high efficiency of using the stone columns to reduce the settlement of the footing on the soft-saturated clay soils.
- The settlement improvement ratio ($K_s$) increases with an increasing diameter of the columns.
- The lateral deformation decreased with an increase in the diameter of the stone column and the shape of the lateral deformation has an irregular shape. The maximum values of the lateral deformation decreased with an increase in the diameter and it occurs at a depth of (1.0 to 1.5) d from the top of the surface.

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