Numerical investigation of granular column-improved soils using the direct shear test

Investigação numérica de solos melhorados com colunas granulares utilizando o ensaio de cisalhamento direto

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ABSTRACT
The granular columns treatment is widely used in the weak soils. The present paper focuses on the numerical modeling of a direct shear test on granular columns in soils. The finite difference code Fast Lagrangian Analysis of Continua in 3 Dimensions (FLAC3D) was used in this research work, to evaluate the equivalent properties of granular column-improved soils with different diameters of the columns, and different plan configurations. The results of these numerical tests are discussed in terms of increases the shear load-strength and decreases the horizontal displacement due to the variation of arrangements, Young's modulus and the friction angle of the granular columns. Different types of failures observed in the granular columns. Bending failure mode is the main in the granular column with large values of Young's modulus and the friction angle when subjected a lateral load.

Keywords: Bending failure, direct shear tests, finite difference methode, granular column, lateral load, shear resistance.
**RESUMO**

O tratamento com colunas granulares é amplamente utilizado em solos fracos. O presente artigo tem como foco a modelagem numérica de um ensaio de cisalhamento direto em colunas granulares em solos. O código de diferenças finitas Análise Lagrangiana Rápida de Contínua em 3 Dimensões (FLAC3D) foi utilizado neste trabalho de pesquisa, para avaliar as propriedades equivalentes de solos melhorados por colunas granulares com diferentes diâmetros das colunas e diferentes configurações de plano. Os resultados destes ensaios numéricos são discutidos em termos de aumento da resistência ao cisalhamento e diminuição do deslocamento horizontal devido à variação dos arranjos, do módulo de Young e do ângulo de atrito dos pilares granulares. Diferentes tipos de falhas observadas nas colunas granulares. O modo de ruptura por flexão é o principal na coluna granular com grandes valores do módulo de Young e do ângulo de atrito quando submetido a uma carga lateral.

**Palavras-chave:** Ruptura à flexão, ensaios de cisalhamento direto, método de diferenças finitas, coluna granular, carga lateral, resistência ao cisalhamento.

**1 INTRODUCTION**

The problem of treatment of soils with granular column has been widely examined. This technique presents an interesting solution for soil stability. Thus, this method is widely used to solve the stability problems of weak soils, by involves replacing a the surrounding soil with a granular material having a high strength. In the literature, many authors have tried to convert the characteristics of the composite material (granular material, soil) with characteristics of an equivalent material. Deb et al. (2012) employed the genetic algorithm method to locate the critical failure surface and optimize the factor of safety for an embankment reinforced by granular columns, constructed on a layer of soft clay. The study demonstrated that a genetic algorithm can be successfully used to locate the critical failure surface in the stone column. In summary, these studies explored different numerical methods, such as the FLAC code and the genetic algorithm, to analyze the stability of an embankment on soft soil treated with stone columns. They contributed to enhancing the understanding of the behavior of such reinforced soil structures and the factors influencing their stability. Chen et al. (2015) conducted physical model tests and 3-D numerical finite element modeling to study the behavior of a uniformly loaded embankment placed on a soft soil treated with geosynthetics encased stone columns. They observed a bending failure of the reinforced columns.
More recently, Mohapatra and Rajagopal (2016) presented a finite difference analysis to study the stability of an embankment constructed on soft clay treated with stone columns encapsulated by geosynthetics. They performed a parametric study on geometric parameters (fill height and spacing of stone columns) and mechanical soil parameters (friction angle of the stone and compressibility of the soft clay).

2 EQUIVALENT AREA METHOD

The 3D problem of a granular column can be converted to an equivalent plane strain problem using the equivalent area method. This method is used to simplify these 2D problems by adopting equivalent properties. The conversion comprises using the equivalent area method. Homogenization consists of replacing the parameters for a composite soil (surrounding soil, granular column) with an equivalent parameter for the improved area having the same physical and mechanical characteristics (Abusharar and Han, 2011; Zhang et al., 2014). In this approach, the properties of the granular columns and the surrounding soil is homogenized.

The equivalent properties \( c_{eq}, \phi_{eq} \) of the improved area can be calculated based on the properties of an individual granular column and surrounding soil and the area replacement ratio \( \alpha \); where \( \alpha \) is the ratio of the total cross-sectional area of the columns to the cross-sectional area of the total improved zone. The equivalent parameters are given by the following equations:

\[
c_{eq} = c_c \cdot \alpha + c_s \cdot (1 - \alpha) \tag{1}
\]

\[
\phi_{eq} = \tan^{-1} \left( \alpha \cdot \tan \phi_c + (1 - \alpha) \cdot \tan \phi_s \right) \tag{2}
\]

Where

\( c_{eq}, c_c, \) and \( c_s \) are the equivalent cohesion and the cohesions of the column and the surrounding soil, respectively; \( \phi_{eq}, \phi_c, \) and \( \phi_s \) are the equivalent friction angle and the friction angles of the column and the surrounding soil, respectively.

The use of powerful equipment in the experimental study of the stability of
structures built on treated soil is extremely costly operation. The mechanical behavior of reinforced soils is very complex, so it is obvious a constitutive model capable of presenting treated soil. Although there are different methods of numerical resolution, when the behavior of the soil is schematized in a non-linear and irreversible way. Numerical, two-dimensional and three-dimensional finite difference modeling codes have experienced a rapid and broad development in the geotechnical engineering. Numerical analyzes are conducted to analyze the stability, the deformation and the influence of several parameters on the response of the model, within reasonable time. In addition, the experimental approach to the study of reinforced soil behavior can provide a validation of the numerical results, an assessment of the importance of each hypothesis adopted in the calculation and finally an in-depth understanding of the problem.

Numerical simulations of experimental testing using a numerical finite element or finite difference software are available in the literature. (Alfaro et al., 1995; Thornton and Zhang, 2003; Liu et al., 2005; Jacobson et al., 2007; Guo, 2008; Mickovski et al., 2011; Mohapatra et al., 2017).

3 PROBLEM PRESENTATION

In this paper, a 3D numerical modeling of the direct shear test on a granular column-treated sand sample with two different arrangements, as illustrated in Figure 1.

The finite difference model of the direct shear test size is (305 x 305 x 140
mm3). The mesh adopted for all cases studied in this paper is refined in the shear plane to capture significant solution accuracy (Figure 1). The sand and the granular columns were modeled by an elasto-plastic model with a Mohr-Coulomb yield criterion and associated flow rule. The simulation of the relative shear deformations between the upper and lower boxes is constrained in the horizontal boundary directions were given to the four vertical sides of box sample, similar to the experimental test conditions. All nodes on the four vertical faces of the bottom box and the bottom surface of the box were given equal displacement in the x direction to simulate shearing of soil during the direct shear test. To simulate the upper shear box’s fixity, all nodes situated on the vertical boundaries of the upper box were constrained from translational movement in the x-direction.

4 VALIDATION OF THE NUMERICAL MODEL

The three models of the ordinary granular columns (50C OGC, 100C OGC, 50T OGC) are adopted to compare the numerical results of this work with those found in the experimental study of Mohapatra et al. (2016), are presented in Table 1.

<table>
<thead>
<tr>
<th>Test arrangement</th>
<th>Notation</th>
<th>Area replacement ratio α (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mm diameter granular column at center</td>
<td>50C</td>
<td>2.11</td>
</tr>
<tr>
<td>100 mm diameter granular column at center</td>
<td>100C</td>
<td>8.44</td>
</tr>
<tr>
<td>50 mm diameter granular columns in triangular pattern</td>
<td>50T</td>
<td>6.33</td>
</tr>
</tbody>
</table>

Source: Authors.

In the present numerical model, an attempt to calculate the shear stress at 75 kPa a normal pressure to each different test arrangement (50C OGC, 100C OGC, 50T OGC). A cylindrical-shaped mesh was employed to discretize the granular columns, while a radially graded mesh was utilized for the sand. The values of the granular column and sand parameters are presented in Table 2.

<table>
<thead>
<tr>
<th>Diameter d [m]</th>
<th>Elastic modulus $E$ [MPa]</th>
<th>Poisson’s Ratio $ν$</th>
<th>Unit weight $γ$ [kN/m$^3$]</th>
<th>Friction angle $ϕ$ [$°$]</th>
<th>Cohesion $c$ [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>-</td>
<td>10</td>
<td>0.30</td>
<td>16.3</td>
<td>29</td>
</tr>
<tr>
<td>Granular columns</td>
<td>0.010</td>
<td>100</td>
<td>0.30</td>
<td>17</td>
<td>48</td>
</tr>
</tbody>
</table>

Source: Authors.
The shear stress curve can be plotted against horizontal displacements as shown in Figure 3.

Figure 3. Shear stress vs. horizontal displacement (σn = 75 kPa).

![Shear stress vs. horizontal displacement](image)

Source: Authors.

The results from the numerical modeling are validated with the laboratory tests carried out by Mohapatra et al. (2016). Figure 3 shows the validation using MC model with the shear stress vs. horizontal displacement plot obtained from the experiments. The numerical tests were concluded when the horizontal displacement of the bottom shear box reached 40 mm. This displacement marked the mobilization of both the peak and critical state shear resistance. It is clear that the three numerical models adopted in this study give results in excellent agreement with results of Mohapatra et al. (2016). Thus, the meshes of the present numerical model give more conservative shear stress values.

The figure also indicates an increase in shear stresses following the arrangement of granular columns within the sand, attributed to the heightened shear resistance of the composite ground (sand-granular column system). The combination of the granular column and surrounding soil functions akin to a composite material, enhancing shear resistance. Elevating the area ratio of granular columns from 2.11% to 8.44% leads to heightened shear resistance, facilitated by a greater proportion of granular column presence within the shear plane. This trend is evident for both 50 mm and 100 mm diameter columns. Interestingly, triangular pattern of 50 mm diameter granular columns exhibit greater
shear resistance than a single column of 100 mm diameter positioned at the center of the box, despite the latter having a higher area ratio. This discrepancy can be attributed to the distribution of deformation resistance points, causing more significant disturbances in displacements, as illustrated in Figure 4.

Figure 4. Horizontal displacement of the different arrangements of OGC: (a) 50T; (b) 100C.

5 EQUIVALENT AREA METHOD VALIDATION

The factors of safety of embankments over stone column-improved soft clay calculated using the equivalent area model were higher those calculated using the individual column model (Abusharar and Han, 2011; Zhang et al., 2014; Labed and Mellas, 2016). The numerical model of this work can verify the certainty of the equivalent area method, using the model of the granular column at the center of the shear box improved soft soil. The area replacement ratio for this verification varies from 0 to 1. The values of the granular column and the soft soil parameters are presented in Table 3.

Table 3. Material properties used in the three dimensional model

<table>
<thead>
<tr>
<th></th>
<th>Elastic Modulus E</th>
<th>Poisson's Ratio ν</th>
<th>Unit weight γ</th>
<th>Friction angle φ</th>
<th>Cohesion c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surrounding soil</td>
<td>5</td>
<td>0,45</td>
<td>16</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>Granular column</td>
<td>20-400</td>
<td>0,30</td>
<td>17</td>
<td>30-45</td>
<td>0</td>
</tr>
</tbody>
</table>

The area replacement ratio is obtained from the circular granular column of diameter dc, with a spacing in both directions s = 305 mm, and replace the geometric dimensions in relations (1, 2), to obtain the theoretical properties of the
equivalent area. The numerical simulations were carried out at three different confining pressures namely 30, 45 and 75 kPa. We can draw the curve of the composite material (granular column, soft soil) shear strength, as illustrated in Figure 5.

Figure 5. Shear stress vs. normal stress curve and shear strength parameters

Figure 6 shows the variation of the numerical and theoretical normalized friction angle and cohesion due to an increase of the area replacement ratio. The area replacement ratio varies from 0 to 1. It is important to note that the effect of the area replacement ratio remains a negligible influence on the composite soil mechanical characteristics when \( \alpha \) ranging from 0 to 0.4; thus, the increase of the mechanical characteristics of soil is particularly weak when the area replacement ratio ranging from 0.4 to 0.7; However, there is a very important influence of the area replacement ratio of the composite soil mechanical characteristics when \( \alpha \) ranging from 0.7 to 1.
6 HORIZONTAL DISPLACEMENTS OF THE COLUMN

6.1 INFLUENCE OF THE AREA REPLACEMENT RATIO

Zhang et al., (2014) noted that the larger diameter of the column, prevents more the horizontal displacements. In order to study the influence of the column diameter on the horizontal displacements of the center, we perform calculations with an area replacement ratio varies from 0.007 to 0.699.

Figure 7 shows the variation of the horizontal displacements of the column obtained from the present study with different area replacement ratio. There was a significant decrease in the horizontal displacements from the area replacement ratio 0.007 to 0.293; However, it should be noted that the influence of the area replacement ratio remains a negligible influence on the horizontal displacements from the area replacement ratio 0.293 to 0.699. Increased the diameter of the column improves its capacity, it is therefore an increase in the mechanical characteristics of composite soil.
6.2 INFLUENCE OF THE GRANULAR COLUMN YOUNG’S MODULUS

The influence of the Young's modulus of the granular column on the horizontal displacement of the granular column is investigated by performing a new series of simulations, a shear box of soft soil treated by a granular column with diameter $d_c = 100$ mm with Young's modulus of the granular column varying between 20 and 400 MPa.

Figure 8 shows the variation of the horizontal displacements of the column as a function of depth for different values of the Young's modulus of the granular column. It can be observed that there is a decrease in the horizontal displacements with increasing Young's modulus of the granular column. This is because the horizontal displacements of the granular column are directly influenced by the stiffness or Young's modulus of the granular column material.

As the Young's modulus of the granular column increases, the granular column material becomes stiffer and less prone to deformation under applied loads. This stiffness effectively reduces the lateral movement of the granular column and decreases their horizontal displacements. However, it can be seen that the moved lower box in the shear plane causes the binding failure of the granular column with important Young's modulus.
6.3 INFLUENCE OF THE FRICTION ANGLE OF THE GRANULAR COLUMN:

To study the influence of the friction angle of the granular column on the horizontal displacements of the column, we perform calculations with a friction angle reaching from 30 to 45 degrees.

Figure 9 illustrates the variation of the horizontal displacements of the granular column as a function of depth for different friction angles of the granular column.
material. It is evident from the graph that there is a decrease in the horizontal displacements for friction angles of the granular column ranging from 30 to 45 degrees. The results suggest that within the range of 30 to 45 degrees, increasing the friction angle of the granular column leads to improved stability, resulting in reduced horizontal displacements. This can be attributed to the increased mobilization of frictional resistance between the granular column and the soft soil, which helps to resist lateral movement. However, beyond a friction angle of 35 degrees, the horizontal displacements start to increase again. This could be due to the formation of a bending failure mechanism in the equivalent columns, which may be less effective in resisting horizontal displacements compared to frictional resistance. Consequently, higher friction angles may lead to a reduction in the overall stability and an increase in horizontal displacements.

The figure also shows that as the friction angle of the granular column increases, the depth at which the maximum displacement occurs also rises. This indicates that a higher friction angle allows the sliding surface to float up in the surrounding soil, resulting in the maximum displacement point shifting upwards.

Furthermore, for larger friction angles, the failure of the column is likely to occur through a bending failure mechanism, which can be seen in the graph.

7 CONCLUSION

From the above study following conclusions can be derived

A triangular pattern of granular columns exhibit greater shear resistance than a single column positioned at the center of the box, despite the latter having a higher area ratio. This discrepancy can be attributed to the distribution of deformation resistance points, causing more significant disturbances in displacements.

A negligible influence on the composite soil mechanical characteristics from the area replacement ratio remains less than 0.4; However, there is a very important influence of the area replacement ratio the composite soil mechanical characteristics when it’s greater than 0.7.

A significant decrease in the horizontal displacements from the area replacement ratio remains less than 0.293; However, it should be noted that the
influence of the area replacement ratio remains a negligible influence on the horizontal displacements from it remains greater than 0.293.

That the move the lower box in the shear plane causes the shearing of the granular column; However, it can be seen that the moved lower box in the shear plane causes a bending failure of the granular column with larger diameter, and prevent more the horizontal displacements.
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