Numerical Analysis of the Influence of Replacement Area Ratio in Foundation Reinforced with Soil Cement Columns

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ABSTRACT

This paper performs a numerical method to analyse the influence of replacement area ratio to behaviours of soft soil foundation reinforced with soil cement columns. The analysis bases on the finite element method (FEM) and Plaxis 2D software to simulate a cylindrical unit cell of soft soil. The cylindrical unit cell includes a soil-cement column and the surrounding soil. In order to estimate the influence of replacement area ratio, the following factors are analysed: the consolidation settlement (the settlement of foundation after consolidation process finished), degree of consolidation, and the improvement factor. Results show that, the replacement area ratio increases, the consolidation settlement increases, accelerate the consolidation process of foundation, also increases the improvement factor. Besides, based on data of this study, an equation fit by regression shows the relationship between the improvement factor and the replacement area ratio.

KEYWORDS: Soil-cement column; the area improvement ratio; the degree of consolidation; finite element method; soft soil improvement

INTRODUCTION

Building construction in delta regions, or riverside areas, where the groundwater is high, one of the key important factors is soft ground improvement. Soft soil with disadvantage properties for constructions, such as low shear strength, high deformability and low permeability, significantly limit the height of construction, lasts excess pore water pressure dissipation process, increases the cost of bulding construction.
Over the last decades, a number of soft soil improvements have applied successfull, for instance, using geosynthetics [Rowe 1984; Borges and Cardoso 2001, 2002], acceleration of consolidation with pre-fabricated vertical drains [Shen et al. 2005], or reinforced with stone columns [Hughes et al. 1975; Priebe 1995], reinforced with soil-cement columns [Rampello and Callisto 2003; Chai J-C 2007], etc. Among of these techniques, using soil-cement columns to improve soft ground is the most popular technique recently, to increase stability and reduce and accelerate settlements. Terashi (2002) showed that “nearly 60% of on-land application in Japan and perhaps roughly 85% of Nordic applications are for the settlement reduction and improvement of stability of embankment by means of group of treated soil columns”.

Numerous studies have been done in the past focusing on the properties of soil-cement, bearing capacity, settlement, and stability of foundation reinforced with soil-cement columns. For example, Lorenzo and Bergado (2004, 2006) studied the fundamental characteristics of cement-treated clays in deep-mixing columns and proposed a method to estimate the strength and compressibility of cement-treated clays. Terashi and Tanaka (1983) and Han et al. (2002) indicated that adding cement into soft soil reduced the permeability of soil. Chew et al. (2004) showed that the cement-treated soil had a higher permeability than the untreated soil, etc. However, limited studies have been conducted on the consolidation of soil-cement columns foundation. Lorenzo and Bergado (2003) based on an analytical solution to predict the consolidation rate of deep mixing column foundations using a unit cell concept. One-dimensional Terzaghi’s solution was used to calculate the consolidation rate of the deep mixing column. Miao et al. (2008) modeled the deep mixing column foundation as a composite foundation with a higher equivalent modulus than the untreated soil and treated the deep mixing column foundation over soft soil as a double layer system. Besides theoretical solutions, numerical solution is used to predicting consolidation of foundation reinforced with soil-cement columns because of its convenience. José Leitão Borges et al (2009) used a computer program incorporates the Biot consolidation theory (coupled formulation of the flow and equilibrium equations) with constitutive relations simulated by the p-q-θ critical state model, to study parametrics of an embankment on soft soils reinforced with stone columns, simultaneously, proposed a new design method related to the settlement improvement factor to the replacement area ratio and the deformability ratio. Yan Jiang et al. (2013) used a mechanically and hydraulically coupled three-dimensional numerical method to evaluated the influence of four key factors to settlement and degree of consolidation of the deep mixed column foundation, by applying commercial finite element software Abaqus.

In this study, using the finite element method (FEM) and Plaxis 2D software to estimate three factors: the consolidation settlement (the settlement of foundation after consolidation process finished), degree of consolidation, and the improvement factor, influenced by the replacement area ratio of an embankment reinforced by soil-cement columns.

NUMERICAL MODELLING

The cylindrical unit cell is used in this numerical study, consisting of one soil-cement column and the soft soil from its influence area. The soil-cement column and its surrounding soil are modeled as elastic materials. Material properties are chosen from an embankment located in Hai Phong city, VietNam. Table 1 lists the parameters of the soil-cement columns and its surrounding soil.
The problem concerns a 3m height embankment on a soft ground reinforced with soil-cement columns. The soft ground is 5m thick normally consolidated clay lying on a rigid and impermeable stratum. The water level is at the ground surface. The soil-cement column depth is 5m, equal to the thick of the soft ground (Fig 1).

Table 1: Material Parameters for the soil-cement column and its surrounding soil

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Name</th>
<th>Foundation</th>
<th>Embankment</th>
<th>Soil-cement</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material model</td>
<td>Model</td>
<td>Mohr-Coulomb</td>
<td>Mohr-Coulomb</td>
<td>Mohr-Coulomb</td>
<td>-</td>
</tr>
<tr>
<td>Type of material model</td>
<td>Type</td>
<td>Undrained</td>
<td>drained</td>
<td>Undrained</td>
<td>-</td>
</tr>
<tr>
<td>Unsaturated Soil unit</td>
<td>$\gamma_{\text{unsat}}$</td>
<td>16</td>
<td>18</td>
<td>18</td>
<td>kN/m$^3$</td>
</tr>
<tr>
<td>Saturated Soil unit weight</td>
<td>$\gamma_{\text{sat}}$</td>
<td>18</td>
<td>20</td>
<td>18</td>
<td>kN/m$^3$</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>$E_{\text{ref}}$</td>
<td>3 000</td>
<td>30 000</td>
<td>120 000</td>
<td>kN/m$^2$</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>$\mu$</td>
<td>0.3</td>
<td>0.3</td>
<td>0.25</td>
<td>-</td>
</tr>
<tr>
<td>Cohesion</td>
<td>$C_u$</td>
<td>1</td>
<td>7</td>
<td>140</td>
<td>kN/m$^2$</td>
</tr>
<tr>
<td>Friction angle</td>
<td>$\phi$</td>
<td>21</td>
<td>25</td>
<td>60</td>
<td>-</td>
</tr>
<tr>
<td>Permeability</td>
<td>$K$</td>
<td>$10^{-6}$</td>
<td>$3.10^{-6}$</td>
<td>$10^{-6}$</td>
<td>m/day</td>
</tr>
</tbody>
</table>

This study uses axisymmetric cylindrical unit cell (Fig. 2). Materials model is Mohr-Coulomb. 15-nodes triangle element is used. The embankment material is modeled as drained; foundation and soil-cement columns material are modeled as undrained behavior. The stage construction of embankment is devided into 6 stages, lasting 30 days. No horizontal displacement is allowed on the vertical boudaries of the mesh while the bottom boundary is completely fixed in both the vertical and horizontal direction (Fig. 2). The ground surface is drainage boundary (the excess pore pressure equals zero), while the vertical and bottom boundaries of the mesh are assumed to be impermeable. The soft ground is assumed to be undrained, with the permeability coefficient in horizontal and vertical directions is the same.

**Figure 1.** Embankment on a soft ground reinforced with soil-cement columns

**Figure 2.** Unit cell

**ANALYSIS OF RESULTS**

The replacement area ratio, $r$, is defined as the ratio between the area of the soil-cement columns, and the improvement area. Considering a unit cell, $r$ is the ratio between cross section area of the soil-cement column, and the area of the unit cell.
where $A_c$ is the cross section area of column; $A_s$ is the area of the soft soil surrounding the column in the unit cell, and $A$ is the cross section area of unit soil.

The replacement area ratio can be changed by varying the spacing between columns with the same column diameter, or by adjusting the diameter of the soil-cement column. The last way seems to be more difficult to do. Therefore, this numerical analysis uses the first way to vary the replacement area ratio. The diameter of soil-cement column is 0.6m. The spacing between columns is different in different cases. Five cases are considered with different values of $r$ in order to analyse the influence of the replacement area ratio, as indicated in Table 2.

<table>
<thead>
<tr>
<th>Case</th>
<th>$r$</th>
<th>d (m)</th>
<th>b (m)</th>
<th>s (m)</th>
<th>t (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0</td>
<td>0.10</td>
<td>0.60</td>
<td>0.95</td>
<td>1.68</td>
<td>1.81</td>
</tr>
<tr>
<td>C1</td>
<td>0.15</td>
<td>0.60</td>
<td>0.77</td>
<td>1.37</td>
<td>1.47</td>
</tr>
<tr>
<td>C2</td>
<td>0.20</td>
<td>0.60</td>
<td>0.67</td>
<td>1.19</td>
<td>1.28</td>
</tr>
<tr>
<td>C3</td>
<td>0.30</td>
<td>0.60</td>
<td>0.55</td>
<td>0.97</td>
<td>1.04</td>
</tr>
<tr>
<td>C4</td>
<td>0.40</td>
<td>0.60</td>
<td>0.47</td>
<td>0.84</td>
<td>0.90</td>
</tr>
</tbody>
</table>

d diameter of soil-cement column; b distance between the symmetry axis and the lateral boundary; s and t spacing between columns in triangular and square grids, respectively.

Consolidation settlement

Figure 3 shows the relationship between consolidation settlement at the surface and the distance from symmetry axis in accordance with different replacement area ratio $r$.

The results from figure 3 show that, as expected, when the replacement area ratio increases, consolidation settlement decreases. For example, settlement on the centre of the column increases 1.68 times (from 9.8mm to 16.5mm) when $r$ changes from 0.4 (case 4) to 0.1 (case C0).

The differential settlement (difference between the average settlement of the soft soil and the average settlement of the column, divided by the average settlement of the unit cell) also
decreases when the replacement area ratio increases, from 35.6% decline to 10.7% in accordance with replacement area ratio varies from 0.1 to 0.4.

**Degree of consolidation**

The average degree of consolidation can be defined via excess pore water pressure, as follows equation:

\[
U = 1 - \frac{\int_0^H u_t dz}{\int_0^H u_0 dz}
\]

(2)

Where \(u_0\) is the initial excess pore water pressure; \(u_t\) is excess pore water pressure at time \(t\); \(z\) is the depth in the foundation from the ground surface; and \(H\) is the softsoil thickness.

However, using the equation (2) to calculate the average degree of consolidation during the entire consolidation process is not convenient, because the average excess pore water pressure profile with depth should be calculated at every moment. Therefore, following equation may be used to estimate the average degree of the consolidation based on the settlement of foundation at time, \(t\):

\[
U = \frac{s_t}{s_f}
\]

(3)

In the equation (3), \(s_t\) is the top surface settlement at time \(t\); and \(s_f\) is the final consolidation settlement when the consolidation is completed.

Figure 4 shows the relationship between the average degree of consolidation and time, with varying in replacement area ratio.

![Figure 4: Degree of consolidation on the ground for cases C0-C4](image)

From above relationship, as expected, the average degree of consolidation of foundation significantly increases with an increase of replacement area ratio. For example, 96% of average degree of consolidation is reached in 50 days for the replacement area ratio \(r=0.4\), but needed 220 days and 410 days for case \(r=0.15\) and \(r=0.1\), respectively. This result implies that the soil-cement columns accelerated the velocity of consolidation process, even though the permeability of the
column was the same as that of the surrounding soil. This conclusion also is in agreement with Huang et al. (2009) and Yan et al (2013).

**Improvement factor**

Improvement factor, \( n \), is defined as the ratio between the settlement of the problem without soil-cement columns and the average settlement of the same problem with soil-cement columns, as following equation:

\[
\frac{s_{\text{funr}}}{s_r} = n \tag{4}
\]

where \( s_{\text{funr}} \) is the settlement of foundation in the unreinforcement case; \( s_r \) is the average consolidation settlement of foundation reinforced by soil-cement columns. According to the definition of improvement factor \( n \), \( n=1 \) when \( r=0 \).

In order to estimate the influence of replacement area ratio \( r \) to the improvement factor \( n \), calculation 12 cases with the value of \( r \) varies from 0 to 1. The results indicate in the figure 5.

![Figure 5: The relation between replacement area ratio and improvement factor](image)

The results of Figure 5 clearly show that the improvement factor significantly increases with the replacement area ratio \( r \). For instance, when the replacement area ratio varies from 0 to 1, the improvement factor significantly increases from 1 to 42. Assume that the correlation between the replacement area ratio and the improvement factor is an exponential function, following function can be regressed: \( n=1.68e^{3.4r} \), with the correlation coefficient \( R^2 = 0.966 \), indicates the correlation is good.

**Conclusions**

In this study, the axisymmetric cylindrical unit cell was used to investigate the influence of replacement area ratio to several factors of embankments on soft soil reinforced with soil-cement columns: the consolidation settlement, degree of consolidation, and the improvement factor. The analyses were performed by a finite element program: Plaxis.

Results revealed that, the replacement area ratio significantly influences to the consolidation settlement, the improvement factor as well as degree of consolidation of foundation. Based on this numerical analysis, the following overall conclusions were confirmed: increasing the
replacement area ratio significantly (1) reduces settlements of foundation; (2) increases the improvement factor and (3) accelerates the consolidation.

REFERENCES


