Study on the settlement and the load-bearing capacity of Long An soft ground reinforced by the stone columns

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ABSTRACT

Soft soil reinforcement methods by using the granular piles are very popular by improving the strength and deformation characteristics of the soft soils. There were many analytical methods such as Aboshi, Priebe, Vesic, Barksdale and Bachus’s method... to estimate the settlement and the load-bearing capacity of soft grounds reinforced by the stone columns. This paper analyzes the applicability of these methods, as well as the finite element method, via software PLAXIS 3D Foundation, with a real construction in Long An, Mekong delta, Viet Nam. The back analysis of measured settlements by applying Asaoka method showed a remarkable difference between the calculated and the observed settlements. The load-bearing capacity tests of the stone columns were carried out to confirm the real bearing capacity and failure mechanism of the stone columns. Finally, the recommendations to determine the settlement and the load-bearing capacity of soft grounds reinforced by the stone columns are proposed.

Keywords: stone columns, settlement, load-bearing capacity, analytical method, shear failure.

1 INTRODUCTION

In order to calculate the load bearing capacity of the stone columns, there are many analytical methods such as Greenwood, Vesic, Barksdale and Bachus’s method. Several methods have been proposed for estimating the settlement of cohesive soils improved by stone columns (e. g Aboshi et al., 1979; Priebe, 1995; Van Impe and De Beer, 1983). The calculated results by these methods are quite different in many cases. In order to evaluate the applicability of these methods, the analyses have been carried out with an actual project. The calculated results have been compared with the results of numerical simulations using finite element method, and the field test results. Based on these analyses, the proposals for calculating the settlement and the load-bearing capacity of soft grounds reinforced by the stone columns have been presented.

2 APPROACH OF SETTLEMENT ANALYSIS

In order to predict the settlement of a soft ground reinforced by the stone columns, there are some well-known methods which are widely used in the world as follows:

Table 1. Typical calculation methods of settlement

<table>
<thead>
<tr>
<th>Method</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equilibrium method</td>
<td>$S_i = m_i (\mu_i \sigma_i) H$</td>
</tr>
<tr>
<td></td>
<td>$R = \mu_i = \frac{1}{1+(n-2)\alpha_i}$</td>
</tr>
<tr>
<td>Priebe method</td>
<td>$1 \over R = 1 + a_i \left[ \frac{v_i + f(\mu_i, \alpha_i)}{(K_A) f(\mu_i, \alpha_i)} - 1 \right]$</td>
</tr>
<tr>
<td></td>
<td>$f(\mu_i, \alpha_i) = \left[ \frac{1 - \mu_i^2}{1 - 2 \mu_i^2} \right] \left[ \frac{1 - 2 \mu_i}{1 - 2 \mu_i + a_i} \right]$</td>
</tr>
<tr>
<td></td>
<td>$(K_A) = \tan^2 \left( 4S^0 - \frac{\phi_t}{2} \right)$</td>
</tr>
<tr>
<td>Granular wall method</td>
<td>$S = RH \left[ 1 - \mu_i^2 \right] \left[ \frac{1 - \mu_i^2}{1 - \mu_i^2} \right] \frac{\sigma}{E}$</td>
</tr>
<tr>
<td></td>
<td>$R = f(\alpha_i, \varphi_t, \mu, \sigma, E)$</td>
</tr>
</tbody>
</table>

3 LOAD-BEARING CAPACITY ANALYSIS OF A SINGLE STONE COLUMN

In case the tip of the stone column is resting on a firm...
Fig. 1. Vesic cylindrical cavity expansion factors.

Fig. 2. Mechanism of failure of short column, Vitkar 1978.

Fig. 3. Bearing Capacity Factor, $N_c$.

Fig. 4. Bearing Capacity Factor $N_\gamma$, $N_q$.
bearing layer, the bulging failure or the shear failure often develops in the improved ground.

3.1 Load-bearing capacity, the case of bulging failure

Vesic, 1972 proposed the formula of ultimate load-bearing capacity as follow:

\[ q_{ult} = \left[ cF'_c + qF'_q \right] \left( \frac{1 + \sin \phi}{1 - \sin \phi} \right) \]  

(1)

where: \( c \) = cohesion, \( q \) = mean (isotropic) stress, \( q = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \) at the equivalent failure depth, \( F'_c, F'_q \) = cavity expansion factors. The cavity expansion factors \( F'_c, F'_q \) shown in Fig.1 are a function of the angle of internal friction of the surrounding soil and the rigidity index, \( I \). The rigidity index, not reduced for the effects of volume change in the plastic zone, is expressed as:

\[ I_e = \frac{E}{(1+v)(c+q \tan \phi_c)} \]  

(2)

where: \( E \) = modulus of elasticity of the surrounding soil in which cavity expansion is occurring, \( v \) - Poisson’s ratio of the surrounding soil.

Besides Vesic, there are also another methods of Greenwood 1983, Hughes 1979, Barksdale and Bachus 1983, etc.…

3.2 Load-bearing capacity, the case of shear failure

Vitkar, 1978 proposed the formula of ultimate load-bearing capacity as follow:

\[ q_{ult} = \frac{I}{2}q_{c,sat}BN_f + cN_c + DfN_q \]  

(3)

where: \( N_f, N_c, N_q \) are bearing capacity factors given in Fig. 3 and Fig. 4.

4 BEHAVIOURS OF STONE COLUMN – IMPROVED SOFT GROUND, A CASE STUDY

4.1 Introduction of a project

With a total area of approximately 64,000m², VIFON II project was planned with two main factories - one for rice-related products and the other for instant noodle products - covered up to 33,000m². Fig. 5 shows the general plan layout of the future project. The factory is designed with different loading areas from 10kN/m² to 40kN/m². The soft ground is reinforced by the stone columns with a diameter of 0.65m and average length of 3.3m. The stone columns are designed and constructed by BACHY SOLETANCHE VIET NAM, and arranged in square grids with the spacing from 1.7m to 2.5m in accordance with each service load case.

4.2 Geological condition

The soil layers and its parameters are shown in Table 2. (Duong Chung Nguyen, 2013).

4.3 Settlement prediction of stone column–improved soft ground

In this part, the settlement of the improved soft ground is calculated by the different analytical methods and the numerical method. Based on the comparison between these results and the measured settlement, the overall assessment of the deformation behavior of stone column – improved soft ground can be concluded.

4.3.1 Analytical results

By applying the different analytical methods mentioned above, the deformation of the improved zone by the stone columns can be calculated according to the 1-D problem with a load of 41.4kN/m². For the unimproved zone which is beneath the stone columns, because the soil layers have deformation modulus of larger than 10Mpa, the deformation of this zone can be predicted by using a Vietnamese Standard TCVN 9362:2012. The settlement determined by the different analytical methods are shown in Fig.6.
4.3.2 Measured settlement at the site

A system of settlement monitoring points was set up to observe the consolidation progress of treated soil as shown in Fig. 7. The settlement monitoring data is measured in a certain period of time and in a certain region. Therefore, the Asaoka method has been applied to determine the final settlement. Fig. 8 shows the final settlement of about 53.4 mm obtained from the S10 region.

4.3.3 Numerical analysis by the FEM

The PLAXIS 3D Foundation software has been utilized to analyze the settlement of an improved ground as shown in Fig. 9. The reinforced ground can be considered to have a behavior of Mohr – Coulomb model. The soil layers and its parameters are shown in Table 1. A calculated area of 144 m² with 25 stone columns has been analyzed in the simulation. The surcharge layer of 2.3 m height caused the settlement of 64 mm as shown in Fig. 10.

* Results Discussion

- The different analytical methods resulted in the similar settlements with a small difference of less than 1%.
- The settlement calculated by the Plaxis 3D Foundation software is very similar to the analytical result, but these results still have a difference of about 16.8% as compared with the observed settlement. The main cause may be due to the fact that the actual
diameter of stone columns is often larger than the designed diameter due to the field compaction. From the in-situ investigation, the actual diameter of stone columns is 754mm which is 13.6% larger than the designed diameter. After the recalculation with the actual diameter of stone columns, the difference between the calculated results and the observed settlement is about 12%.

4.4 Determination of the load bearing capacity of a single stone column

In this part, the load-bearing capacity of the stone columns is calculated by the different methods. Based on the obtained results, the overall assessment of the failure mechanism as well as the load bearing capacity of stone columns can be concluded.

4.4.1 Analytical results

Depending on the different mechanisms of failure, the ultimate load bearing capacity determined by the different analytical methods are shown in Table 3.

<table>
<thead>
<tr>
<th>Method</th>
<th>Mechanism of failure</th>
<th>Ultimate load bearing capacity, $P_{ult}$ (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenwood 1970</td>
<td>Bulging failure</td>
<td>17.5</td>
</tr>
<tr>
<td>Vesic 1972</td>
<td>Bulging failure</td>
<td>19.4</td>
</tr>
<tr>
<td>Hughes 1979</td>
<td>Bulging failure</td>
<td>16.1</td>
</tr>
<tr>
<td>Barksdale and Bachus 1983</td>
<td>Bulging failure</td>
<td>16.2</td>
</tr>
<tr>
<td>Vitkar and Madhav 1975</td>
<td>Shear failure</td>
<td>10.55</td>
</tr>
</tbody>
</table>

4.4.2 Static load test

After finishing the test column, a static load test as shown in Fig. 11 has been conducted to determine the in-situ load bearing capacity of the stone column. In the experiment, the loading process is divided into 6 levels of 33kN, 66kN, 99kN, 133kN, 165kN, 199kN which correspond to the pressures of 40.7kN/m$^2$, 81.5kN/m$^2$, 122.1kN/m$^2$, 164.2kN/m$^2$, 203.7kN/m$^2$, 245.7kN/m$^2$, respectively. From the graphs in Fig. 13 and Fig. 14, the ultimate load bearing capacity of a stone column, $q_{ult}$, can be obtained.

4.4.3 Numerical analysis by the FEM

The PLAXIS 3D Foundation software has been utilized to analyze the load bearing capacity of a single stone column as shown in Fig. 15. Using a reinforced concrete slab with a thickness of 0.3m, 0.9m in width and length set up on the top of the stone column with a real diameter of 0.754m. Based on the relationship between load and settlement of a stone column as shown in Fig. 16, the load bearing capacity of 98kN can be determined.
Based on the relationship between load and settlement as shown in Fig. 16, if a stone column is considered as a concrete pile in the load bearing capacity determination, this may result in a large difference of about 140% between the calculated result and the field test result.

Fig. 15. A 3D finite element modelling was used to determine the load bearing capacity of a single stone column.

Fig. 16. Relationship between load and settlement of a stone column.

5 CONCLUSION

Based on the analyses of settlement and load bearing capacity of Long An soft ground reinforced by the stone columns, the main conclusions are as follows:

- The different analytical methods resulted in the similar settlements, but the Aboshi’s method with its simplicity is a good practical approach for the engineers.

- The settlement calculated by the Plaxis 3D Foundation software is very similar to the analytical result, but these results still have a difference of about 16.8% as compared with the observed settlement. The main cause may be due to the fact that the actual diameter of stone columns is often larger than the designed diameter due to the field compaction. After the recalculation with the actual diameter of stone columns, the difference between the calculated results and the observed settlement is about 12%.

- The analyzing the relationship between load and displacement of a stone column to predict the load-bearing capacity by applying the Plaxis 3D Foundation software may result in a big error. There is a large difference of about 140% between the calculated result and the field test result.

- Among the analytical methods, the results of Vitkar and Madhav (1975) method are quite similar with the results of the static compression test with a difference of about 6.6%. In this case, the actual failure of a single stone column may have a mechanism of shear failure. In the calculation of the load-bearing capacity of a stone column, if the column tip penetrates into a stiff layer, the bulging failure or the shear failure often occur.

REFERENCES


