Sensitivity Study of the Bearing Capacity and Pile-soil Stress Ratio for Aeolian Sand Foundation Treated with CFG Piles

Yugen Li¹, Deyi Zhang²* and Changyan Wu³

¹Department of Architecture Engineering, Yulin University, China
²Department of Engineering Mechanics, Ontario Power Generation, Ontario, Canada
³College of Civil and Architecture Engineering, Xi’an University of Science and Technology, China

Corresponding author (Email: zhangdyhit@gmail.com)

Abstract: In order to study the bearing characteristics of Aeolian-sand composite foundation, including the influence and sensitivity of the foundation settlement and pile-soil stress ratio, this paper presents experimental and numerical studies of Aeolian-sand foundation treated with CFG piles (CFG single pile and composite foundation). The numerical results agree well with the in-situ load tests. Effect of pile spacing, cushion thickness & modulus, length of pile, pile diameter and tip soil parameters such as the Poisson’s ratio and soil modulus on both the composite foundation ultimate load bearing capacities and pile-soil stress ratio were analyzed. The results reveal that CFG pile has a critical length and the design equations by the code lie in the safe side. Pile spacing, cushion thickness and pile diameter affect the pile-soil stress ratio significantly. The thickness of cushion layer, the length of pile and the pile diameter also have significant effects on the compound foundation settlement. The CFG pile composite foundation can indeed enhance the load-bearing capacity of Aeolian-sand significantly.

Key words: CFG pile, Aeolian-sand, load-bearing capacities, pile-soil stress ratio, sensitivity

1. INTRODUCTION

CFG piles foundation are composed of relatively small diameter, short piles made of C15-C25 cemented fly-ash gravel with a spacing of 1-2m and a replacement ratio of approximately 2–3% to form a much stronger pile-soil composite foundation (Shuang, 2014). Because of the construction convenience and low cost, it has been extensively used to support the upper structure systems with independent, strip, box and raft foundations in Northern China since 1990s, where the foundation soil is mostly suitable for the construction of CFG piles. In recent years, it has become much more attractive and has been widely adopted in the low high-rise building foundations with unfavorable geological site conditions including sand, silt, clay, silt soil and miscellaneous fills. The practical application of CFG pile foundation demonstrated that its load-bearing capacity can be significantly increased since the cushion layer within the CFG composite foundation can help load being distributed to both the CFG pile and surrounding soil domain.

2. STATE OF THE ART

CFG pile composite foundation is new and the mechanism is different from the traditional foundation so that they become the hot research spots. Gong et al (2007) and Yan et al (2006) considered that the bearing capacity and deformation calculations are two major issues in the design of CFG pile composite foundation. Wang et al (2013) used the model test method to investigate the stress and displacement of the foundation pile retaining structure based on a high-rise building foundation treated with CFG piles. Zhao et al (2010) introduced the elastic-plastic load transfer model to propose a method to calculate the composite foundation settlement considering the interaction of pile-soil-cushion system and the results obtained are in good agreement with the measurement data. Cai et al (2015) analyzed the influential factors of the CFG pile’s bearing capacity and the settlement for the highway, where obtains a reasonable range of parameters such as CFG pile length, pile spacing and thickness of cushion has been obtained. Wang et al (2012) and Wen et al (2012) investigated the pile-soil stress ratio of CFG pile composite foundation under high-speed railway. Xu et al (2016) took the railway subgrade treated with “CFG pile + compaction pile” as an example, presented the calculation method of composite modulus for the composite foundation settlement, and the result agreed well with the engineering practice. Yang et al (2008) used a finite difference method to simulate the deformation and the stress characteristics of both the CFG single pile and the composite foundation, revealing that the pile stress mainly concentrates on the region within the range of half of the pile length. Zhang et al (2011) analyzed the influential mechanism of various cushion materials and thickness on the pile-soil stress ratio of CFG pile composite foundation based on the finite element software ABAQUS. Cao et al (2011) established a fuzzy reliability analysis method of the CFG pile composite foundation bearing capacity on the basis of cut-set theory and interval calculation rule, which can evaluate the bearing capacity of the composite foundation more accurately.
Chen et al (2006) adopted a boundary load correction coefficient and corrected the calculation formula of composite foundation bearing capacity of CFG pile, which can better reflect the size of the bearing capacity of the foundation. Li et al (2016) investigated the bearing properties of Aeolian-sand foundation with the CFG pile. Wang et al (2009) analyzed the influence of the design parameters on the composite foundation of CFG pile through numerical simulation, which provided a basis for the optimization design of the soft soil foundation. The influence of both the layer stiffness and the negative friction on the pile-soil stress ratio and the bearing properties of CFG pile composite foundation were analyzed (Tian, 2014; Sheng, 2008), and the conclusions are of great value to improve the theory of composite foundation.

However, only very few researches considered the sensitivity studies of the influence on the pile-soil stress ratio and bearing properties of CFG pile composite foundation resulting from various factors. What is more, the research on the Aeolian-sand composite foundation is rarely reported. This paper takes the foundation of the No.14 Residential Building in Yulin City, Shaanxi Province, China as a research object, and a sensitivity analysis was carried out to explore the influences of various factors on both the bearing properties and pile-soil stress ratio.

This paper is organized as follows: Section 3 described the engineering case, solved the ultimate bearing capacity of CFG single pile and composite foundation using the finite difference software FLAC3D based on the in-situ load tests and compared with the theoretical calculation values. In Section 4, the influence trend and sensitivity of various factors on both the settlement and pile-soil stress ratio of composite foundation were analyzed. Section 5 summarized the research results from this study.

3. ENGINEERING DESCRIPTIONS AND EXPERIMENT

Because of Aeolian-sand’s special physical & mechanical properties and complex mineral elements, the bearing capacity of both the CFG single pile and composite foundation is the other soft soil foundation. The ultimate bearing capacity of single pile and composite foundation by the numerical simulation method based on the in-situ load tests were calculated. The result shows that the bearing capacity of both single pile and composite foundation calculated by the Chinese code was more conservative.

3.1. Project overview

The project is located in Hong Hill in the Northeast of Yulin City, Shaanxi Province, China. It is a shear wall type building structure having a total of 24 stories and 2 stories underground. The geotechnical conditions at Hong Hill were used for investigation. This site is a typical desert wind landform and the ground surface is covered with a large amount of Aeolian-sand, so that the cohesion of the site is small and the natural bearing capacity is lower. Table 1 shows the parameters of the physical and mechanical properties of the main soil layer, where the density of the soil sample was measured by the sand-pour method and the shear strength index was determined by the triaxial test showing in Figures 1-2. According to the design requirement, if the site is not well treated by engineering measures, it normally can’t meet the load bearing capacity requirements for this residence building.

<table>
<thead>
<tr>
<th>Soil name</th>
<th>$\phi$ /$^o$</th>
<th>$c$ /kPa</th>
<th>$\rho$ /kg.m$^{-3}$</th>
<th>$f_{sk}$ /kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>① plain fill ($Q_1^{ml}$)</td>
<td>16</td>
<td>4.5</td>
<td>1650</td>
<td>60</td>
</tr>
<tr>
<td>② silt ($Q_2^{al}$)</td>
<td>23.5</td>
<td>7</td>
<td>1780</td>
<td>110</td>
</tr>
<tr>
<td>③ fine sand ($Q_3^{eol}$)</td>
<td>19</td>
<td>0</td>
<td>1810</td>
<td>120</td>
</tr>
<tr>
<td>④ fine sand ($Q_4^{al}$)</td>
<td>22</td>
<td>0</td>
<td>1830</td>
<td>150</td>
</tr>
<tr>
<td>⑤ fine sand ($Q_5^{al}$)</td>
<td>23</td>
<td>1.5</td>
<td>1850</td>
<td>160</td>
</tr>
<tr>
<td>⑥ silt ($Q_6^{al}$)</td>
<td>26</td>
<td>12</td>
<td>2030</td>
<td>175</td>
</tr>
</tbody>
</table>
3.2. Design of composite foundation

According to the design requirement, the composite foundation is treated with CFG piles. The pile diameter is 0.5m and the pile length is 15m with buried length of 11.3m deep; the triangular layout is adopted with a center distance of piles 1.5 m; the sixth silt layer is designed as the tip pile layer; each pile is required to have a bearing capacity of 870kN and the foundation of 470kPa according to the geological exploration data. Figure 3 shows the overall layout for the No.14 Residential Building and its composite CFG pile foundation.

3.3. In-situ load tests

After completion of the construction, six test points are randomly selected to carry out the in-situ load tests by the stacking platform method shown in Figure 4. For the single pile test, three points are labeled as S2, S4, S6, and for the composite foundation test, other three points are labeled as S1, S3, S5, respectively. All of the test points were loaded by the QYL320 hydraulic jacks with the settlement dial with measuring range from 0 to 30mm. The single pile is loaded linearly increasing with an increment 1/10 of the required design bearing capacity of the single pile by a rigid loading plate on top of the pile, which is termed as ten-level loading. Similarly, the composite foundation (single pile with cushion on top) is loaded with an eight-level loading by a circular loading plate whose area is the same as a single pile’s treatment area through a under coarse sand screed. The testing time, stable standard, terminating conditions of the test are in accordance with the Chinese design code (JGJ79-2012). The Q(P)-S curves are shown in Figures 5-6 (Q denotes the load applied on the single pile and P denotes the load applied on the composite foundation. S denotes the movement of the pile under the applied load Q or P). In Figures 5-6, curves of S2, S4 and S6 represent the settlement of single pile testing points and curves of S1, S3 and S5 represents the settlement of composite foundation at the testing point. For convenience of analysis, Figures 5-6 also present an average settlement from various measurement points of the single pile and composite foundation.
As seen from the Q(P)~S curves in Figures 5~6, during the loading processes, the settlement of both CFG single pile and composite foundation gradually increase with a stable pattern. At the initial loading stage, the curves of Q(P)~S show an approximately linear variation. When the loading reaches two times of the required design bearing capacity, the curves did not show obvious inflection points (the settlement of S6 is the largest in the curve of Q-S and so is S5 in the curve of P-S, far less than the termination load value given in design code), meaning that the soil is basically in the elastic deformation stage and the actual bearing capacity of both the single pile and composite foundation are higher than the required. This experimental observation validates the findings presented in a majority of the studies (JGJ79-2012) that the design of the composite foundation bearing capacity is more conservative. Therefore, it is necessary to reveal the ultimate bearing capacity of the composite foundation through the numerical way.

The load test results show that the bearing capacity of the Aeolian-sand composite foundation treated with CFG pile can meet the bearing capacity of design requirements and increase significantly. In this case, the bearing capacity of composite foundation is more than 470kPa, far greater than the natural bearing capacity of 175kPa without CFG pile (increased about two times). The first reason is that the vibrational loading during the construction makes the original sand structure destroyed so that the sand particles become more stable and dense, causing the increase of the composite foundation’s bearing capacity. Another reason is, both the mineral composition of pile and the water in soil undergo the hydrolysis, the hydration and the pozzolanic reaction, such as the hydrated calcium silicate \( (3CaO.2SiO_2.3H_2O) \), the hydrous aluminum acid \( (3CaO.Al_2O_3.6H_2O) \), the aqueous iron acid calcium \( (3CaO.Fe_2O_2.6H_2O) \) and other insoluble material were generated, the chemical reaction equation is given in Equation (1). Therefore, the gelation area of soil increased and the composite strength indicators improving, then the bearing capacity of composite foundation has been enhanced and it was found that the tricalcium aluminum is the major factor affecting the strength of the composite foundation.

\[
Ca^{2+} + 2(OH)^{-} + Al_2O_3 \rightarrow CAH
\] (1)

3.4. Modeling and ultimate bearing capacity calculate
As seen from the in-situ load tests results in Figures 5~6, the soil is basically in the elastic stage at the end of the loading. The finite difference software FLAC3D is applied to analyze the ultimate bearing capacity of both the CFG single pile and the composite foundation. In the analysis, it is assumed that both the single pile and the cushion are elastic material while the soil is an elastic plastic material with Mohr-Coulomb material model. The boundary of the subsoil model were restrained by the pin supports, the front, the rear, the left and the right boundaries were restrained by the roller supports. Moreover, the contact interaction models are selected for the contact surface between the pile and the soil, the soil and the cushion, as well as the cushion layer and the pile body. The model dimension is chosen to be 18 times of the pile diameter along the horizontal direction and two times of the pile length along the vertical direction with seven piles of the triangle layout, where the diameter of the pile is 0.5m, the spacing of the pile is 1.5m and the length of pile is 15m. Figure 7 shows the overall model configuration and Figure 8 shows the schematic diagram for the contact surface. The physical parameters used in the numerical modeling are listed in Table 2.

**Table 2. The Physical Parameters of The Numerical Model**

<table>
<thead>
<tr>
<th>soil name</th>
<th>$K$ / MPa</th>
<th>$G$ / MPa</th>
<th>$\nu$</th>
<th>$\phi$ /°</th>
<th>$c$ / kPa</th>
<th>$\rho$ / kg $m^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>fine sand</td>
<td>13.3</td>
<td>8.0</td>
<td>0.25</td>
<td>23</td>
<td>1.5</td>
<td>1860</td>
</tr>
<tr>
<td>silt 1</td>
<td>15</td>
<td>6.92</td>
<td>0.30</td>
<td>26</td>
<td>10</td>
<td>2050</td>
</tr>
<tr>
<td>silt 2</td>
<td>15</td>
<td>6.92</td>
<td>0.30</td>
<td>26</td>
<td>10</td>
<td>2050</td>
</tr>
<tr>
<td>CFG pile</td>
<td>1.2*104</td>
<td>9.17*103</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>2500</td>
</tr>
<tr>
<td>cushion</td>
<td>1.25*102</td>
<td>5.77*10</td>
<td>0.3</td>
<td>24</td>
<td>-</td>
<td>2100</td>
</tr>
</tbody>
</table>
To verify the numerical model, the ultimate bearing capacity of single pile is simulated by the stress loading method by changing the concentrated load to the axial stress on the top of the pile when loading with a coefficient of 10.19. It was loaded according to the in-situ load tests condition after the gravity stress was balanced until the model was damaged, and the Q–S curves are shown in Figure 9.

For the composite foundation, according to the construction, 0.3m thick coarse sand cushion is set at the top of the pile, and a circular rigid loading plate is loaded according to the load level. The numerical result of P–S curve was shown in Figure 10.

As seen from Figure 11 and Figure 12, the Q (P)–S simulation curves of both CFG single pile and the composite foundation agree well with the average settlement of the in-situ load test. The deviation of the settlement of single pile is about 4.9%, while that of the composite foundation is approximately 5.1%. According to the Chinese design code, the CFG pile bearing capacity obtained from the in-situ test is $2816/2=1408$ kN, which tends to the 43.5% more than the design bearing capacity of 981.1kN by the Equation (2) of the design code. Similarly, for the composite foundation, the bearing capacity obtained from the in-situ test is approximately 1060kPa, which is 71.5% more than the design bearing capacity of 618kPa by the Equation (3) of the design code. It indicates that the actual ultimate bearing capacities of the composite foundation and the single pile from the in-situ test are greater than the design capacity results given by the code. The design values are more conservative, suggesting that the evaluation of the bearing capacity of the CFG pile Aeolian-sand composite foundation should be determined comprehensively by both the in-situ load tests and numerical analysis method.

$$R_u = u_p \sum_{i=1}^{n} q_{si} l_{pi} + \alpha_p q_p A_p$$  \hspace{1cm} (2)

Where
- $u_p$ - pile perimeter, m;
- $n$ - soil layers divided along the pile;
- $q_{si}$ - shaft resistance eigenvalue of the $i$ layer in pile lateral soil, kPa;
- $\alpha_p$ - efficiency factor of the pile resistance;
- $l_{pi}$ - thickness of the $i$ layer soil, m;
- $q_p$ - tip resistance eigenvalue of pile, kPa.

$$f_{spk} = \lambda m \frac{R_u}{A_p} + \beta(1-m)f_{sk}$$  \hspace{1cm} (3)

Where
- $\lambda$ - efficiency factor of bearing capacity of a single pile;
- $R_u$ - bearing capacity of a single pile, kN;
- $A_p$ - pile cross-sectional area, $m^2$;
- $\beta$ - efficiency factor of the bearing capacity of soil between piles;
- $m$ - area replacement ratio of a single pile;
- $f_{spk}$ - characteristic value of composite foundation bearing capacity, kPa;
4. RESULT ANALYSIS AND DISCUSSION

Settlement and pile-soil stress ratio is the two important indicators to measure the CFG pile composite foundation. The pile spacing, cushion thickness & modulus, pile length, pile diameter, as well as the tip soil parameters such as modulus and Poisson’s ratio are significant elements to both of them. Therefore, analyzes the trends and sensitivity of effects on both the settlement and pile-soil stress ratio under these factors is quite necessary.

4.1. Effect of pile spacing

Pile spacing is a main factor to influence the bearing capacity of composite foundation. That’s because the area displacement ratio is anti-related with the pile spacing. In this case, we chose three sets of pile spacing 1.2m, 1.5m and 1.8m to analyze the tendency and sensitivity on the settlement and pile-soil stress ratio, and the results are shown in Figures 11-12.

As seen from Figure 11, the settlement of composite foundation decreased with the pile spacing increasing, and the bigger the pile spacing is, the more sensitive it is. The main reason is that the pile spacing is an important factor to affect the area replacement ratio, which determines the strength of composite foundation largely. But we also see a phenomenon, it is not wise to improve the bearing capacity of composite foundation by reducing the pile spacing blindly. Because it’s too conducive to play the bearing capacity of inter-pile soil when pile spacing is smaller.

Figure 12 shows the relation between the pile-soil stress ratio and pile spacing, we can see the pile-soil stress ratio increasing with the increase of pile spacing, the bigger the pile spacing is, the larger the pile-soil stress ratio is, the more obvious the sensitive is. That’s because the pile-soil stress ratio correlates negatively with the area replacement ratio, and the area replacement ratio is inversely proportional to the square of pile spacing.

Figures 11-12 indicate that the reasonable pile spacing is existed when processing the Aeolian-sand foundation with CFG piles. This is an important conclusion for the project design.

4.2. Effect of cushion parameters

Cushion is the core technology of CFG pile composite foundation, which would significantly affect the both foundation settlement and pile-soil stress ratio. In the parametric studies, the thickness of cushion varies from 0.15m to 0.40m with an increment of 0.05m and its elastic modulus varies from 90MPa to 180MPa by an increment of 30MPa. The effect of the cushion parameters on both the settlement of composite foundation and pile-soil stress ratio was analyzed, and the results are shown in Figures 13-16.
As seen from Figure 13 and Figure 15, the settlement of the composite foundation correlate with the cushion thickness and the modulus inversely. As they are relatively small, the settlement is more sensitive to the variation of cushion parameters. When the cushion thickness becomes 0.3m or more to 0.4m and the cushion modulus to 150MPa or more up to 180MPa, the effect of the cushion thickness and modulus is negligible on the P-S curves. It reveals that the CFG pile composite foundation has a critical thickness of cushion and elastic modulus in dealing with Aeolian-sand foundation. However, the settlement is bigger than the single pile model at the same load level because of the pile group effect (Li, 2016). As seen from Figure 14 and Figure 16, similar conclusion can be drawn for the pile-soil stress ratio.

However, for the pile-soil stress ratio, it decreases first and then increases with the increase of both the cushion thickness and the modulus (it decreases while the cushion thickness is below 0.2m and the modulus below 90Mpa). The reason the pile-soil stress ratio decreases first with the increase of cushion is that, the bearing capacity of the inter-pile soil is too late to play a role for the loading when the cushion thickness is smaller. At this time, the load is mainly supported by the top of the pile. When the loading gradually increase, the bearing capacity of inter-pile soil increases and has a greater increase than the stress on the top of the pile. Meanwhile, the puncture could occur easily on top of pile when the cushion modulus is smaller, and at this time, the upper load was mainly taken by the pile. Then the bearing capacity of inter-pile soil increases as the loading increases and faster than stress on the top of the pile. That is the reason why the pile-soil stresses ratio decrease first with the modulus. The above explanations can be seen from Figures 17-18 accordingly.
4.3. Effect of pile length

Some researches show that the CFG pile composite foundation has obvious characteristics as a frictional pile, the longer the pile is, the higher the bearing capacity of composite foundation is. But other researchers conclude that there is a critical pile length in treatment of the foundation with CFG piles. In this case, the length of the pile increases from 6m to 18m with an increment of 3m. The analysis results for the effect of pile length on both the settlement and pile-soil stress ratio of the composite foundation are shown in Figures 19-20.

As seen from Figure 19, when the pile length is smaller, its influence on the settlement of composite foundation is more obvious, with an inverse correlation to the settlement values. Within the reasonable pile length, the longer the pile is, the smoother the P-S curve of the composite foundation, and the higher the ultimate bearing capacity. However, at certain length, the bearing capacity does not improve significantly. It indicates that a critical length of the pile exists in terms of the treatment of the CFG pile with Aeolian-sand foundation, which resulted from the sand shear expansible properties.

It is shown in Figure 20 that the pile-soil stress ratio correlates positively with the pile length. The shorter the pile length is, the more significant its influence is. When the pile is up to a certain value, its effect appears to become minimal and the curves are nearly parallel. On the one hand, it shows that the friction properties of the CFG pile is obvious. On the other hand, it indicates that the critical pile length exists in the treatment of the Aeolian-sand foundation.

4.4. Effect of the pile diameter

The bearing capacity of CFG pile composite foundation is largely determined by the area replacement ratio. If the pile spacing, pile length and the methods of pile arrangement are the same, the pile diameter is the only factor to determine the replacement ratio. Six kinds of pile diameter parameters, including 0.35m, 0.40m, 0.45m, 0.50m, 0.55m and 0.60m, are considered for both the deformation and pile-soil stress ratio of composite foundation, as shown in Figures 21-22.

It is seen from Figure 21 that the pile diameter has a larger influence on the composite foundation settlement. Under the same pile length, the greater the pile diameter is, the smaller the composite foundation.
settlement will be, and the higher the ultimate bearing capacity. The reason lies in the significant effect of the pile body for the higher area replacement ratio of the large pile diameter.

It is concluded from Figure 22 that the pile-soil stress ratio correlates negatively with the pile diameter. The smaller the pile diameter is, the greater the pile-soil stress ratio is. This is attributed to the stress concentration caused by the tip of the pile. It should be noted that the pile-soil stress ratio become stably while the pile diameter lies above 0.45 to 0.60m.

Figures 21-22 also show that the increase of pile diameter can reduce the settlement of composite foundation and adjust the pile-soil stress ratio, but when its value reaches a certain threshold, the effect is not significant. This is the main reason for accounting for the replacement ratio in the Chinese design code (JGJ79-2012).

4.5. Effect of tip soil parameters

The properties of pile tip soil also have an important influence on the ultimate bearing capacity of CFG pile composite foundation and the pile-soil stress ratio. Four kinds of pile tip soil modulus (15MPa, 20MPa, 25MPa and 30MPa) are analyzed. Also, the effect of Poisson’s ratio corresponding to these four tip soil modulus on the settlement of CFG pile composite foundation are provided, for Poisson’s ratios including 0.20, 0.25, 0.30 and 0.35. The analytical results are presented in Figures 23-26.

As seen from Figure 23, the composite foundation settlement is in inverse correlation to the pile tip soil modulus, the bigger the modulus is, the smaller the composite foundation settlement and the smaller the sensitivity. The rate of variation of the settlement is much smaller than that of the modulus increase rate. As seen from Figure 24, the pile-soil stress ratio positively correlates with the size of pile tip soil modulus. The relationship between Poisson’s ratio of pile tip soil and the composite foundation settlement and the pile-soil stress ratio are given in Figures 25-26. The settlement is in inverse correlation with the Poisson’s ratio, but positive correlation with the Poisson’s ratio for the pile-soil stress ratio. These observations reveals that the CFG pile has certain characteristics as an end bearing pile, meaning that the pile tip soil layer has certain significance to improve the bearing capacity of the Aeolian-sand composite foundation and adjust the pile-soil stress ratio.
5. CONCLUSION
To explore the ultimate bearing capacity of CFG single pile and composite foundation, the numerical simulation is used based on the in-situ load tests of Aeolian-sand treated with CFG piles. It mainly discussed the sensitivity influence of various parameters such as the pile spacing, cushion thickness, pile length, replacement ratio, etc. through the established model on both the settlement and pile-soil stress ratio. The conclusions drawn from this research are:

The bearing capacities of both the CFG single pile and composite foundation suggested by Chinese design code are conservative. It is recommended that the similar Aeolian-sand foundation bearing capacity be determined by a combination of the in-situ load test and numerical analysis approach.

(2) Because the sand can exhibit expansible property, the CFG pile treated with the Aeolian-sand foundation has a critical length. When the pile length exceeds this limit value, the change of the length has minor effect on the bearing properties of composite foundation.

(3) Both the composite foundation settlement and pile-soil stress ratio is sensitive to the cushion thickness and area replacement ratio.

(4) The bearing capacity of Aeolian-sand composite foundation is significantly improved when the CFG pile is used.

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