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Numerical simulation and analysis on the factors affecting the Bearing Capacity of bag-grouting-pile composite foundation

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ABSTRACT

In order to study the key factors affecting the bearing capacity of bag-grouting-pile composite foundation (BGP-CF), numerical simulation and field test were conducted under the background of a subgrade project in which BGP was used to reinforce the subgrade, a model for calculating pile-soil parameters for BGP-CF was built, the results of numerical simulation were compared and verified against those of field test, and the effects of pile diameter, pile length, grouting pressure and the coefficient of friction at pile-soil interface on the bearing capacity of BGP-CF were analyzed. The results of comparison and verification indicate that the bearing characteristics of BGP-CF can be simulated and reproduced effectively by means of numerical simulation. The results of numerical simulation show that the bearing capacity of BGP-CF can be improved slightly by increasing pile diameter and grouting pressure, and can be increased significantly by increasing pile length, and particularly, by ensuring that the lower pile end is located in tight soil and by increasing the coefficient of friction at pile-soil interface.

Keywords: bag grouting pile; composite foundation; affecting factors; numerical simulation

1. INTRODUCTION

BGP refers to a new technology that combines soft soil grouting technology with the application of geotextile [1]. The main working principle of BGP-CF can be elucidated as follows: slurry is injected into the geotextile bags pre-embedded in soft soil to expand the geotextile bags and compact the soil, the injected slurry hardens in the bags as water separates from it, forming a body of hardened slurry with a regular cylindrical shape or a shape like a string of bottle gourds, which forms a CF together with the surrounding soil, thus achieving the purpose of soil reinforcement. Therefore, such foundations usually exist in the form of “pile-soil CF” in fields. Extensive research efforts have been conducted on BGP. Ge[2], Ye[3] et al. firstly discussed the conditions for application of BGP and pointed out that such piles could be used to treat soft soil foundations and soft foundations with thick and deep interlayers. Tang[4] and Wu[5] further studied the construction techniques for BGP, determined the specific construction parameters and proposed the quality inspection methods for BGP. Li[6] analyzed the properties and reinforcing effect of bag grouting piles. Most studies mentioned above are mainly targeted at the conditions for application and construction techniques for BGP, and there have been no systematic research findings on the bearing capacity of BGP-CF, which restricts its progress and extensive application.

Due to the influence of field conditions and the restriction in the construction of pile foundation (PF), normally it is impossible to analyze and study the problems with PF and CF in a comprehensive manner, especially in field test[7]. With the continuous development of computer technology in recent years, numerical simulation has become a alternative method that can be used to study such problems with PF, which has already investigated by various experts and scholars. For PF, Wang[8] studied the problem of reinforcement with double rows of piles in deep. Also, Lai[9] investigated seismic protection with double rows of anti-slide piles. For CF, Chen[10] discussed the problem of settlement of CF with gravel piles in soft soil, while Lei[11] examined the soil compacting effect of CF with pipe piles. Moreover, Chen [12] analyzed the bearing capacity of CF with reinforced gravel piles under vertical load. It is worth noted that all investigations mentioned above were based on the technology of numerical simulation.

Additionally, the research findings of Zhou[13], Zheng [14] and Ding[15] indicate that the main factors affecting the bearing capacity of pile-soil CF are pile diameter, pile length, grouting pressure, and the coefficient of friction at pile-soil interface. Therefore, under the background of a subgrade project in which BGP was used to reinforce the subgrade, a pile-soil calculation model for BGP-CF was built and the effects of pile diameter, pile length, grouting pressure and coefficient of friction at pile-soil interface on the bearing capacity of such CF were studied and analyzed using numerical simulation software ANSYS based on the results of field single pile statistic load test.

2. Engineering background

2.1 Geologic conditions

The numerical simulation of BGP-CF was conducted under the background of a subgrade project located on one side of the Huangpu River, Shanghai, China. The test area is a coastal plain, one of the four major geomorphic units in Shanghai. According to the project geotechnical report and the results of cone penetration test and laboratory tri-axial test, the distribution, and the physical and mechanical parameters of various soil layers in the test area are determined, as listed in Table 1.

Table 1 Depth and Parameters of Soil Layers

Soil layer	Modulus of compressibility/MPa	Cohesion /kPa	Average thickness /m
Silty clay	3.37	18.0	0~2
Mucky silty clay	2.58	12.0	2~5
Mucky clay	2.72	7.0	5~10
Silty clay	2.53	8.6	10~13
Silt	6.80	10.8	13~16
Silty clay	3.63	17.3	16~19
Silty clay interlayered with siltstone	4.92	13.0	>19

2.2 Pile construction parameters

Piles were constructed in a standard way in accordance with the specifications set out in the Cylindrical Bag Grouting Method [1]. The grouting hole diameter, design buried depth of pile, pile diameter, grout amount, borehole diameter are 300 mm, 15 m, 400 mm, 1.88 m^3, and 200 mm, respectively. The P.O 43.5 ordinary Portland cement was used. The grouting pressure is 0.4 MPa, unidirectional permeable bag was used with shear strength, frontal puncture strength no less than 0.9 kN and 5.0 kN, respectively. The friction factor is about 0.55.

2.3 Single pile static load test

The bearing capacity of the BGP-CF was determined by means of single pile static load test according to Technical Code for Ground Treatment (DG/TJ08 -40-2010) and the Code for Engineering Geological In-situ Testing for Railways (TB10018-2003). The test was carried out by slow loading method using a bearing plate with an area of 0.8 m × 0.8 m. The estimated load range for single pile static load test was determined to be 0~640 kPa according to the project design requirements. The estimated load was applied in 16 stages at a load increment of 40 kPa at each stage. The pile was unloaded at a single-stage load decrement two times the single-stage load increment.

3. Numerical simulation

3.1 Numerical simulation programs

The bearing capacity of the BGP-CF was numerically simulated using the ANSYS software. The main factors affecting the bearing capacity of

CF with compaction piles, in terms of pile diameter, pile length and side friction should be considered [13-15]. Since the friction of BGP is determined by grouting pressure and the coefficient of friction at pile-soil interface, 14 numerical simulation programs divided into four groups were designed to evaluate these factors. The details of these programs are given in Table 2, in which the preset parameters of programs 2, 5, 10 and 13 are consistent with those for single pile static load test carried out in the field.

Table 2 Schematic diagram of simulation programs and research parameters

No.	Grouting pressure /MPa	Pile diameter /mm	Pile length /m	Coefficient of friction
1	0.4	300	15	0.55
	0.4	400	15	0.55
	0.4	500	15	0.55
2	0.4	400	12	0.55
	0.4	400	15	0.55
	0.4	400	18	0.55
	0.4	400	21	0.55
3	0.2	400	15	0.55
	0.3	400	15	0.55
	0.4	400	15	0.55
	0.5	400	15	0.55
4	0.4	400	15	0.3
	0.4	400	15	0.55
	0.4	400	15	0.8

3.2 Pile-soil contact setting

Pile-soil contact setting is critical in simulating the bearing capacity of CF. Thus, a "target surface" and a "contact surface" were defined, which refer to the pile body (including the pile side and body) and the soil, respectively. Moreover, the "target surface" was simulated by "TARGE170" unit, while the "contact surface" was simulated by "CONTA173" unit. The mechanical analysis of the "target surface" and the "contact surface" was conducted using the augmented Lagrange method. In real applications, it is believed that after pile-soil contacting, initial cohesion C is mainly contributed by the water segregated from the geotextile bags in a unidirectional way and cement slurry. Therefore, the initial cohesion could be set as $C \approx 0$[10-12]. In pile-soil contact analysis, the value of maximum allowable shear stress TAUMAX was determined to be the standard value of ultimate side friction given in Table 1 and the coefficients of sliding friction between the pile and soil were determined to be the coefficients of friction at pile-soil interface for various programs listed in Table 2, which were adapted from Ref. [16] and Ref. [17]

3.3 Equivalent grouting pressure simulat-eon method

Since the ANSYS software could not well simulate the dynamic lateral pressure induced expansion, the equivalent simulation method may be alternative for simulating the grouting pressure. The expansion of geotextile bags after grouting was simulated by applying temperature rise   to the pile unit to generate a volumetric increment, i.e.:

$$\Delta T = \frac{p}{E \cdot \alpha} \quad (1)$$

where E is the modulus of elasticity of pile material,   is the coefficient of thermal expansion of pile material, and p is the grouting pressure.

3.4 Numerical simulation model

Both the pile and the soil were numerically simulated with "SOLID45" unit[10-12]. For the numerical simulation of the elasto-plastic stress and strain of soil around the piles in CF, the Drucker-Prager (DP) yield criteria are usually adopted. In addition, it is pointed out[13-15] that for CF, the horizontal impact range will generally not exceed 10 times pile diameter and the vertical impact range will generally not exceed 1/3 of pile length. Therefore, a 6 m × 6 m square area around the pile (12 times the maximum design area) was determined as the area to be analyzed in the horizontal direction and the length from the surface to 10 m below the lower pile end (1/2 of the maximum design length) was selected as the area to be analyzed in the vertical direction. Due to the symmetry of load and computational model, 1/4 of the model was selected as the final simulation model to reduce the software's computational load. Here, the final simulation model for program 02 and the grids thereof are presented, as shown in Fig. 1, which consists of 1252 pile units and 4232 soil units.

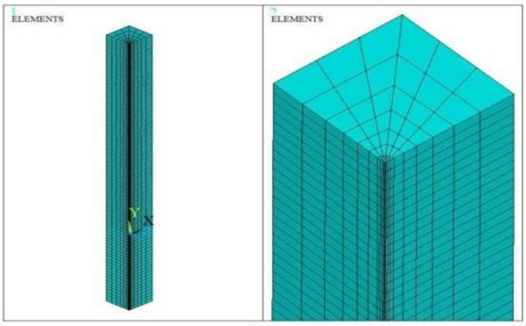

Fig 1 Overall and partial schematics of finite element model for numerical simulation of bag grouting piles

The material and mechanical parameters of bag grouting pile determined listed in Table 3, which are adapted from Ref. [1]. The load area and program were arranged according to the requirements for single pile static load test in the field.

Table 3 Material Mechanical Parameters of Bag Grouting Pile

Material	Modulus of elasticity /MPa	Poisson's ratio	Coefficient of thermal expansion
Hardened paste of fly ash cement slurry	2.0×10^4	0.20	6.78

4. Numerical simulation and verification of single pile CF

The results of numerical simulation with program 2 were compared with the results of single pile static load test conducted in the field. The results show that the vertical displacement of the numerically simulated pile and surrounding soil in stage-16 static load test, see Fig 2 and 3. In addition, Fig. 3 shows the comparison between the measured values and numerical simulation results of P-S curves for the composite foundation.

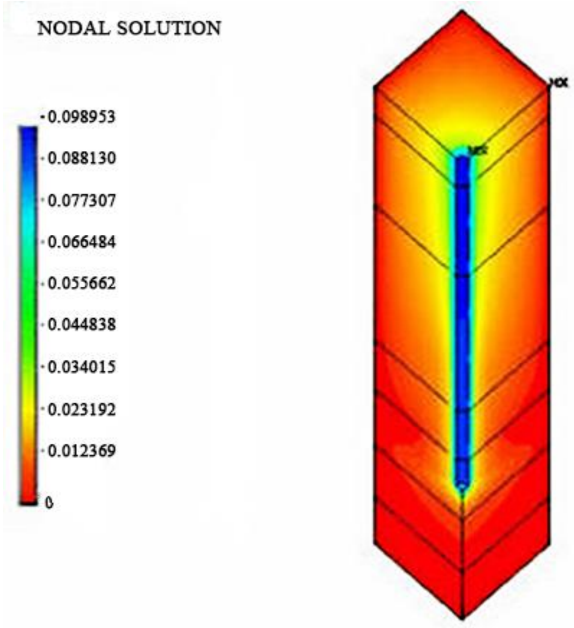

Fig. 2 Numerical simulation of the composite foundation in the 16-stage static load test

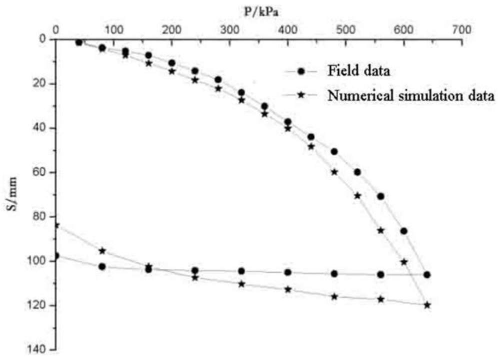

Fig. 3 Comparison between the measured values and finite element calculated values of P-S curve

In Fig. 2, at loading stage 16, the maximum settlement of the pile is 88.9mm, which is basically consistent with the real result. The comparison of P-S curves shown in Fig. 3 indicates that the numerical simulation results are consistent with the real loading and unloading processes, and the curves have remarkable sections of decline after loading and spring-back after unloading. For the decline sections, the numerical simulation results are consistent with the actual P-S curves, both of which show remarkable "turning points", and the deviations of the numerical simulation results from the measured values are ＜12%. For the spring-back sections, there are great deviations between the numerical simulation results and the measured values, but the trends of changes shown in the numerical simulation results and the measured values are consistent and "rising points" appear at the end of spring-back sections. The measured values and numerical simulation values of the bearing capacity of the composite foundation are listed in Table 4 and are consistent with each other. These results indicate that the results of single pile statistic load test can be effectively reproduced by setting reasonable numerical simulation parameters, and it is practicable to use numerical simulation method to study the factors affecting the bearing capacity of BGP-CF.

Table 4 Comparison between measured values and finite element analysis results

Value	Maximum settlement/mm	Ultimate bearing capacity of composite foundation/kPa
Measured value	106.	555
Finite element calculated value	119.7	515.28

5. Results and discussion

5.1 Effect of pile diameter on the bearing capacity of BGP-CF

The results of numerical simulation with program 1 are shown in Fig. 4 and the calculated values of the ultimate bearing capacity of the BGP-CF are recorded in Table 5.

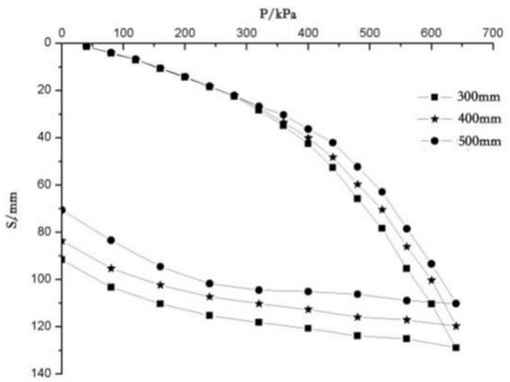

Fig. 4 Numerical simulation of P-S curve results under different pile diameter conditions

Table 5 Analysis of numerical simulation results under different pile diameter conditions

No.		Pile diameter/mm	Maximum settlement /mm	Ultimate bearing capacity of composite foundation/kPa
1		300	124.9	508.17
		400	119.7	515.28
		500	117.2	517.43

In Fig. 4, it can be found that as pile diameter increases, the ultimate bearing capacity of the CF increases and the spring-back after unloading also increases, but such trend of increase mainly occurs after the "turning point". This indicates that the increase in pile diameter has significant effect only when plastic failure occurs in the soil around the pile or relative slipping occurs between the pile and soil. In Table 5, it can be found that as pile diameter increases from 300 mm to 500 mm (by 66%), the ultimate bearing capacity of the CF increases by 9.26 kPa (1.8%), indicating that the ultimate bearing capacity is linearly and directly proportional to pile diameter. However, from the perspective of relative increment, the effect of pile diameter on the ultimate bearing capacity of the CF is slight. In real applications, increased pile diameter will require more grouting material, which is not economic, and the pile weight will also increase, resulting in the reduction of the bearing capacity of CF to a certain extent. Therefore, it is not recommended to increase the ultimate bearing capacity of CF by increasing pile diameter in real applications.

5.2 Effect of pile length on the bearing capacity of BGP-CF

The results of numerical simulation with program 2 are shown in Fig. 5 and the calculated values of the ultimate bearing capacity of BGP-CF are recorded in Table 6.

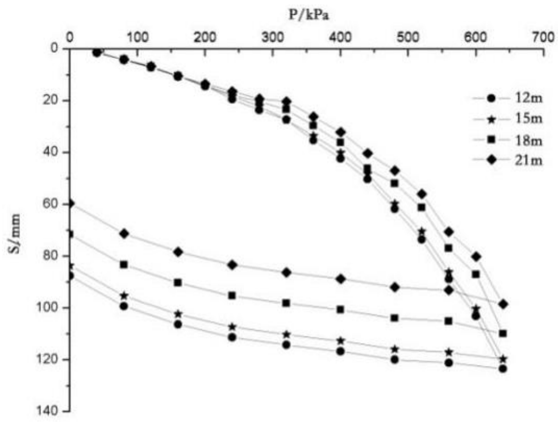

Fig. 5 Numerical simulation results of P-S curve under different pile length conditions

Table 6 Analysis of numerical simulation results under different pile length conditions

No.	Pile length/mm	Maximum settlement /mm	Ultimate bearing capacity of composite foundation/kPa
2	12	123.4	509.44
	15	119.7	515.28
	18	109.9	533.21
	21	98.4	564.17

In Fig. 5, it can be found that the increase in pile length has significant effect on the ultimate bearing capacity of the CF both before and after the "turning point". In Table 6, it can be seen that as pile length increases from 12 m to 21 m (by 91%), the ultimate bearing capacity of a single pile increases significantly by 53.73 kPa (11.4%), especially after pile length increases to 18 m. The reason is that the lower pile end is in the tight soil layer with silty clay and siltstone interlayered with silty clay, and the bearing capacity of single pile CF is improved significantly thereby. These results are consistent with the investigation by Murugesan et al [7].

5.3 Effect of grouting pressure on the bearing capacity of BGP-CF

In order to analyze the effect of grouting pressure on the bearing capacity BGP-CF, the results of numerical simulation with program 3 are plotted in Fig. 6 and the calculated values of the ultimate bearing capacity of the are recorded in Table 7.

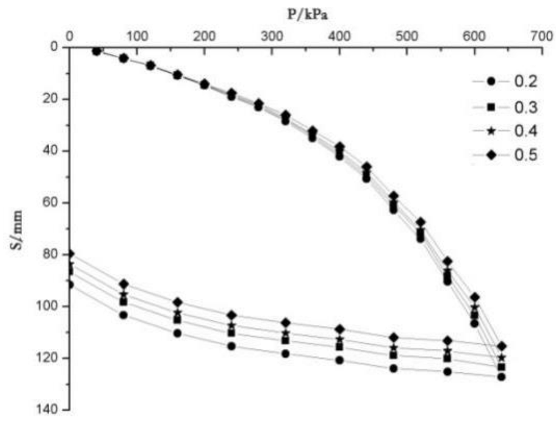

Fig. 6 Numerical simulation results of P-S curve under different grouting pressure conditions

Table 7 Analysis of numerical simulation results under different grouting pressure conditions

No.	Grouting pressure / MPa	Maximum settlement /mm	Ultimate bearing capacity of composite foundation/kPa
3	0.2	127.2	507.02
	0.3	123.4	512.28
	0.4	119.7	515.28
	0.5	115.3	519.47

In Fig. 6, it can be found that as grouting pressure increases, the ultimate bearing capacity of the CF increases and the spring-back after unloading also increases, but such trend of increase is not obvious. In Table 7, it can be seen that although the ultimate bearing capacity of the CF increases (by 9.45 kPa) as grouting pressure increases (from 0.2 MPa to 0.5 MPa), the relative increment is very small (the ultimate bearing capacity increases by only 2% when grouting pressure increases by 150%). These results indicate that the ultimate bearing capacity of the CF can be improved to a certain extent by increasing grouting pressure, but in real applications, excessively high grouting pressure tends to result in pipe or bag breaking and the effect of increased grouting pressure on the ultimate bearing capacity of the CF is not significant. Therefore, in practice, it is not recommended to increase the ultimate bearing capacity of CF by increasing grouting pressure.

5.4 Effect of the coefficient of sliding friction at pile-soil interface on the bearing capacity of BGP-CF

In order to analyze the effect of the coefficient of sliding friction at pile-soil interface on the bearing capacity of BGP-CF, the results of numerical simulation with program 4 are plotted in Fig. 7 and the calculated values of the ultimate bearing capacity are recorded in Table 8.

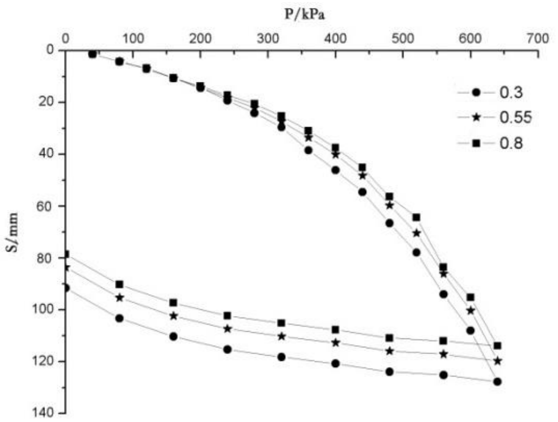

Fig. 7 Numerical simulation results of P-S curve under different pile-soil sliding friction coefficients

Table 8 Analysis of numerical simulation results under different pile diameter conditions

No.	Coefficient of sliding friction	Maximum settlement /mm	Ultimate bearing capacity of composite foundation/kPa
4	0.3	127.7	506.17
	0.55	119.7	515.28
	0.8	111.9	541.23

In Fig. 7, it can be seen that as the coefficient of friction increases, the ultimate bearing capacity of the CF increases and such increase is consistent with that contributed by increased pile diameter, and such trend of increase mainly occurs after the "turning point" (as the mode of friction changes from static friction to dynamic friction), which is consistent with the field test result. In Table 8, it can be observed that as the coefficient of sliding friction at pile-soil interface increases from 0.3 to 0.8 (by 160%), the ultimate bearing capacity of the CF increases by 35.06 kPa (7%). Additionally, from the comparison between Fig. 7 and Table 8, it can be found that at a fixed grouting pressure, the ultimate bearing capacity of single pile composite foundation increases linearly with the increase in the coefficient of friction, and as grouting pressure increases, the ultimate bearing capacity of the CF increases more significantly with the increase in the coefficient of friction. Therefore, in real applications, increased coefficient of sliding friction at pile-soil interface can improve the bearing capacity of BGP-CF more effectively than increased grouting pressure and improved geotextile property.

6. Conclusion

In this study, a pile-soil calculation model for composite foundations with bag grouting piles (BGP-CF) was built and the effects of pile diameter, pile length, grouting pressure and the coefficient of friction at pile-soil interface on the bearing capacity of such foundations were analyzed using numerical simulation software ANSYS. The most important conclusions are summarized as follows:

(1) The results of comparison between the numerical simulation results and the measured values show that the bearing characteristics of single pile CF can be effectively reproduced by setting reasonable numerical simulation parameters, and it is practicable to use numerical simulation method to study the factors affecting the bearing capacity of BGP-CF.

(2) The bearing capacity of BGP-CF can be improved slightly by increasing pile diameter. However, the increase in pile diameter will lead to higher quantity of pile material and larger pile weight, thus affecting the cost effectiveness of projects in real applications. Therefore, it is not commended to increase the ultimate bearing capacity of BGP-CF by increasing pile diameter.

(3) Pile length has significant effect on the bearing capacity of BGP-CF. The most effective way to increase the bearing capacity of such CF is to increase pile length to ensure that the lower pile end is located in a tight soil layer.

(4) The bearing capacity of BGP-CF can be improved by increasing grouting pressure and the coefficient of sliding friction at pile-soil interface. However, the numerical simulation results show that at a fixed grouting pressure, the ultimate bearing capacity of single pile CF increases linearly with the increase in the coefficient of friction, and as grouting pressure increases, the ultimate bearing capacity of the CF increases more significantly with the increase in the coefficient of friction.

Compared with grouting pressure, the coefficient of sliding friction at pile-soil interface has more significant effect on the bearing capacity of BGP-CF. Increasing grouting pressure to excessively high levels may result in pile or bag breaking, therefore, it is recommended to increase the bearing capacity of such CF by increasing the coefficient of sliding friction at pile-soil interface.

7. ACKNOWLEDGMENTS

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