Numerical analysis of XCC pile group effect and bearing capacity of piled raft foundation

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Abstract. A series of three-dimensional numerical models were established based on the field test to study the interaction of pile-raft-soil system in X-section cast-in-place concrete (XCC) piled raft foundation. The analysis of influence factors of XCC pile group effect was carried out by introducing the interaction factor of piles, and the bearing capacity of XCC piled raft foundation was discussed through comparison with XCC elevated pile foundation and single XCC pile foundation. The computed results shown that the pile location, pile number, pile and soil modulus ratio and pile spacing had a certain effect on the XCC pile group effect. The raft had a negative effect on the bearing capacity of XCC piled raft foundation compared with the foundation without rafts. The ultimate bearing capacity of XCC piled raft foundation was larger than that of XCC elevated pile foundation because the raft and pile of XCC piled raft foundation could provide stronger constraints on the soil between piles and strengthened it.

1. Introduction

With the increasing scale of infrastructure construction, it is inevitable to carry out the engineering construction on soft soil. Over the years, a new efficient pile type called X-section cast-in-place concrete (XCC) pile had been widely used in the treatment of soft soil in China, such as 312 National Motorway, the Fourth Bridge of Yangtze River and the Jiangshan Road [1-3]. The installation of XCC pile is performed by driving a hollow, X-section mold with a pyramidal flap as presented in Fig. 1, and three control geometrical parameters which are outside diameters a, spine width b and open arc angle θ are used to establish the size of the section. Both of the side friction and the moment of inertia are increased by making full use of the side surface area of the XCC pile compared with the circular pile with equal cross-section area.
At present, many studies have been carried out about the special cross-section piles, for instance, H pile [4-6], tapered pile [7-9], belled pile [10-12] and pipe pile [13-15]. Seo et al. [4] carried out the laboratory axial load tests on H-section piles and compared the test results with those predicted by soil properties and field test-based methods. Bryden et al. [7] proposed a new theoretical model for the axial stiffness and damping parameters of tapered piles. Lee et al. [8] developed an analytical model through the Runge-Kutta method and the Regula-Falsi method to predict the buckling behavior of tapered piles embedded in inhomogeneous soil. Moayedi et al. [10] performed a series of model tests and Finite element modeling (FEM) analysis on belled piles in loose sand, and found that the pile with installed belled could reduce 75% of the soil surface deformation compared to the straight pile. Liu et al. [13] simulated the interaction of soil and pipe pile under small deformations by introducing the additional mass considering the inertia and damping effect of soil plug.

XCC piles, like other special cross-sectional piles, were designed to improve the bearing capacity more effectively. Lv et al. [1] proposed that the XCC pile could significantly increase the ground-bearing capacity by conducting a series of static load tests. The stress transfer mechanism of XCC pile and piled raft foundation were explored using analytical solution and numerical analysis [16]. The installation effect of XCC pile in soft soil ground was also discussed and a framework for understanding the non-circular cross-section penetrator problem was offered [17-19]. Sun et al. [20] provided an insight into a ballastless track of XCC piled raft foundations using theoretical analysis and calculation. However, these studies mainly focused on the single XCC pile and piled raft foundation, the XCC pile group and piled raft foundation had not been explored deeply.

In this research, a series of numerical models of XCC pile group and piled raft foundation were established based on the field test, using the finite difference software FLAC 3D, and qualitative analysis of the interaction between soil and piles was carried out to reveal the XCC pile group effect. The bearing capacity of XCC piled raft foundation was also studied considering the pile-soil-raft interaction. This study can provide some reference for the design of XCC pile group and piled raft foundation.

2. Establishment and validation of the numerical model

2.1. Field test

The field test was performed in the Qiaobei sewage treatment plant near the Venice Water Town in Nanjing, China. The groundwater under the site was permeable along the depth direction, and it had no corrosive effect on the reinforced concrete structures. Fig. 2 shows the static penetration curve of
the site by cone penetration tests (CPT). The distribution of soil layers from top to bottom is shown in Table 1. The XCC piles with outside diameter 530 mm, spine width 110 mm, open arc angle 90 degrees, pile spacing 1.85 m, and pile length 10.5 m were adopted in the sedimentation tank of the sewage treatment plant. The numbering method of the XCC pile group foundation with sixteen piles is shown in Fig. 3, and it is similar to the pile group foundation with four piles. Static load test of pile foundation was performed to obtain the load-settlement curves of No. 2 pile as shown in Fig. 3. The designed bearing capacity of the pile was 120 kPa, and ten vertical loading grades were utilized to the pile, which was $Q/Qu = 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.25$, and $2.50$, where, $Q$ was an external vertical load on the pile, $Qu$ was the designed bearing capacity of XCC piles. The next load stage was applied when the dial indicator was stable for more than half an hour. The corresponding control group was the equal-section area circular piles with a diameter of 426 mm. The pile spacing, pile length and loading steps were the same as those of XCC piles.
### Table 1. Soil layers of the test location.

| Type of soil | Unit weight/\(\text{kN/m}^3\) | Cohesion /kPa | Effective friction angle/° | Young’s modulus/MPa |
|--------------|-----------------------------|---------------|---------------------------|---------------------|
| Fill         | 17.8                        | 17.6          | 25.9                      | 11.88               |
| Silty clay   | 17.8                        | 17            | 17.4                      | 10.70               |
| Mud          | 17.6                        | 9             | 15.6                      | 8.32                |
| Silty sand   | 19.3                        | 6             | 30.6                      | 19.02               |
| Silty sand   | 19.2                        | 7             | 31.3                      | 25.60               |
| Mud          | 17.6                        | 9             | 15.6                      | 8.32                |
| Fine sand    | 18.9                        | 6             | 30.7                      | 28.12               |
| Fine sand    | 18.9                        | 5             | 31.2                      | 28.12               |

#### 2.2. Introduction of the numerical model

2.2.1. *Program of numerical study.* Based on the field test, two parts of numerical studies were performed to investigate the response of XCC pile group and piled raft foundation due to an axially load using FLAC 3D. In the first part, a series of three-dimensional models of XCC pile and soil were established to study the interaction between XCC piles, and only half of the field test area was considered in order to improve the efficiency of simulation calculation for the symmetry of load and piles. In the second part, the other series of three-dimensional models of XCC pile, raft and soil were built to analyze the bearing capacity of XCC piled raft foundation. And only a quarter of the field test area were simulated because the whole research object including load was a symmetric structure.

2.2.2. *Pile geometry, finite element mesh and boundary and initial conditions.* The geometric parameters of piles in the three dimensional model were the same as those of field tests. In the first part, the entire 16 XCC pile finite element model was 20 m long, 10 m wide and 22 m high with a total of 33,526 nodes and 29,416 units as shown in Fig. 4. In order to analyse the influence of raft on the vertical bearing capacity of XCC piled raft foundation, pile caps of XCC elevated pile foundation was considered as a raft, and its physical and mechanical properties were the same as those of raft in the second part. Table 2 summaries all the numerical analyses carried out in the second part.

![Figure 4. Finite element mesh in the first part: (a) front view; (b) plan view.](image)
Table 2. Statistical table of 3-D models in the second part.

| No. | Pile number | Arrangement | Pile length/m | Pile spacing/m | Pile type | Raft area/m² |
|-----|-------------|-------------|---------------|----------------|-----------|--------------|
| 1   | 0           | Raft        | -             | -              | -         | 12×12        |
| 2   | 1           | Single pile | 12            | -              | -         | -            |
| 3   | 4×4         | square      | 12            | 1.5            | Piled raft foundation | 6×6        |
| 4   | 4×4         | square      | 12            | 2.1            | Piled raft foundation | 8.4×8.4    |
| 5   | 4×4         | square      | 12            | 3              | Piled raft foundation | 12×12      |
| 6   | 4×4         | square      | 12            | 1.5            | Elevated pile foundation | 6×6        |
| 7   | 4×4         | square      | 12            | 2.1            | Elevated pile foundation | 8.4×8.4    |
| 8   | 4×4         | square      | 12            | 3              | Elevated pile foundation | 12×12      |
| 9   | 2×2         | square      | 8             | 2.1            | Piled raft foundation | 4.2×4.2    |
| 10  | 2×2         | square      | 10            | 2.1            | Piled raft foundation | 4.2×4.2    |
| 11  | 2×2         | square      | 12            | 2.1            | Piled raft foundation | 4.2×4.2    |
| 12  | 2×2         | square      | 14            | 2.1            | Piled raft foundation | 4.2×4.2    |
| 13  | 4×4         | square      | 8             | 2.1            | Piled raft foundation | 8.4×8.4    |
| 14  | 4×4         | square      | 10            | 2.1            | Piled raft foundation | 8.4×8.4    |
| 15  | 4×4         | square      | 14            | 2.1            | Piled raft foundation | 8.4×8.4    |

As for the boundary conditions, it was specified that all points of the symmetry and boundary plane had a velocity of zero in the vertical direction. The maximum unbalanced force was used as the convergence criterion in this research, and once it was satisfied, the calculation was terminated and the simulation process was considered to have reached equilibrium. With respect to the initial conditions, the self-stress balance of soil was carried out to reach the ground stress balance firstly, and then the pile or the pile and raft were added to balance the ground stress again.

2.2.3. Constitutive model and model parameters. The Mohr-Coulomb model was used in the soil, and which was simulated as elasto-plastic materials. The parameters of the soil are presented in Table 1. Young's modulus of soil layers were reckoned by result that was acquired from the CPT test, and the poisson ratio was set to 0.3. The pile and raft were simulated as elastic material, being coincident with the field test, the Young's modulus, poisson ratio and unit weight were 30 GPa, 0.2 and 25.0 kN/m³, respectively. The interface between pile and soil was set up using the contact element without thickness in FLAC 3D, and the Coulomb shear model was adopted. The cohesion and effective friction angle of the interface was 4.5 kPa and 24°, respectively.

2.2.4. Modelling procedures. The step of ground stress balance was carried out before the general pile load steps. After that, ten load grades that were similar to the field test were applied onto the pile separately, which was $Q/Qu = 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.25, \text{ and } 2.50$, where, $Q$ was an external vertical load on the pile, $Qu$ was the designed bearing capacity of XCC piles in field test. Afterwards the unloading steps corresponding to the loading steps were run to remove all the loads that had been applied.

2.3. Validation of the numerical model

The numerical simulation were carried out for No. 2 pile, which was the same as the pile studied in the field test. The pile types included XCC and circular piles. The load-settlement curves of the field test were compared with that of numerical simulation results, as shown in Fig 5. In the figure, DS and DR stood for the circular pile with equal cross-section area and circular pile with equal outside diameter, respectively, and the meaning was adopted in the following discuss in this paper. At the settlement of 5 mm, the numerical results of the circular pile with equal cross-section area were about 20% larger
than the test result, and then the difference between them gradually decreased. When the settlement was 25-30 mm, the numerical results basically coincided with the test results. The load continued to increase, the difference remained in a small range that could be accepted. As for the XCC pile, the test and numerical results agreed well in the whole loading process, though there was a small difference at the settlement about 10-25 mm and 35-45 mm.

The load-settlement curves of test and numerical results of circular piles with equal cross-section area were under that of XCC piles in the full load range, and the load-settlement curve of the numerical results of circular pile with equal outside diameter was located above that of XCC pile. Both of which were consistent with the previous research results [16]. In conclusion, the numerical results were coincident with the experimental results. The model was viable to serve as the basis for further research.

3. Analysis of XCC pile group effect

The pile-soil system is an important part of piled raft foundation, so it is necessary to study the pile group effect in pile-soil system. This section focused on the XCC pile group effect in pile-soil system, and the effect of pile location, pile number, pile space and pile and soil modulus ratio on the capacity of piles was explored. The interaction factor of piles presented by McCabe and Lehane [21] was adopted to this section for the quantitative analysis, which can be defined as:

\[ \alpha = \frac{\omega_c}{\omega} \]  

(1)

Where \( \omega_c \) is the displacement of the pile head under load, \( \omega \) is the displacement of other pile head not under load.

3.1. Effects of pile location

Fig. 6 presents the variation of interaction factors of piles in different locations due to the advancement of load. In the figure, X stood for the XCC pile, and the number 2, 5 and 9 meant the location of piles as shown in Fig. 3. No. 0 was a loaded pile and the other piles were non-loaded piles. Piles on symmetry axis (No. 2, 5, 9) were selected for study, it could be seen that the interaction factors decreased with the increasing load for XCC pile, and the difference of interaction factors between No. 2, 5, 9 piles were negatively related to the advancement of load. This might be due to the decrease of common deformation capacity of pile and surrounding soil with the increasing load. It could also be found that the sensitivity of interaction factors to load change were negatively related to the distance from No. 0 pile. This could be explained as the additional stress generated by vertical load decreased, and finally approached zero as the distance from pile No. 0 increased.
Figure 6. Load-interaction factors curve of various types and locations.

The change laws of DS pile and DR pile were consistent with that of XCC pile. However, under the same load, the interaction factors of DS pile were much smaller than that of XCC pile, and the difference increased along the increasing distance from No. 0 pile. This was because the circumference of XCC pile was 1.3 times that of DS pile, and the side resistance of XCC pile was larger, which made the additional stress at the same point of non-loaded XCC pile greater and the interaction between two piles enhanced. The interaction factors between DR and XCC piles had little difference, which was mainly due to the same cross-section circumference and the similar side friction of them.

3.2. Effects of pile number

XCC pile group models of four piles (2 × 2), nine piles (3 × 3) and sixteen piles (4 × 4) were used for analysis in this part. Fig. 7 illustrates the mobilization of interaction factors of piles in different locations and different pile groups with the increase of load. In the figure, the number in front of “-” meant the number of piles, and the number behind it meant the location of piles as shown in Fig. 3.

Figure 7. Load-interaction factors curves of various numbers and locations.

The interaction factors of XCC piles in the same pile location decreased with the increase of pile number, and the degree of this change was negatively correlated with the load. This could be attributed to that the other unloaded piles had an opposite effect on the studied unloaded pile. Taking No. 2 pile as an example, when there were four piles in the pile group, No. 0 pile was subject to upward friction because it was a loaded pile, while the other non-loaded piles were subject to downward friction, therefore, the effect of the non-loaded piles on No. 2 pile was opposite to that of No. 0 pile on No. 2 pile. Also, when there were nine piles in the pile group, No. 0 pile was subject to upward friction, while the other non-loaded piles were subject to downward friction. The effect of these non-loaded piles on No. 2 pile was opposite to that of No. 0 pile on No. 2 pile. The situation was similar with that
of sixteen piles. Fig. 7 also showed that the effect of pile number on the interaction factor of XCC piles was limited.

3.3. Effects of pile-soil modulus ratio

From the conclusion above, pile number had limited effect on the interaction factors of XCC piles. In order to improve the calculation efficiency, the XCC pile group foundation was arranged squarely with four piles (2×2) and a pile spacing of 2.5 m only in this section. A homogeneous soil was set up to eliminate the interference of other conditions to the study, and the effect of the pile-soil modulus ratio was explored by changing the modulus of soil. The results are shown in Fig. 8.

![Figure 8. The relationship of pile-soil modulus ratio and interaction factors.](image)

It was found that the effect of pile-soil modulus ratio on the interaction factor was related to the loading conditions. When the load was 128 kN to 512 kN, the interaction factors decreased with the increase of pile-soil modulus ratio. This was because the proportion of the pile end resistance increased with the increase of pile-soil modulus ratio, thus the side friction and the interaction factors of piles decreased. When the load was greater than 512 kN, the interaction factors first increased and then decreased as the pile-soil modulus ratio increased, and the change range was small. This was due to the pile side resistance had been fully exerted when the load was large, at this time, the end resistance of piles played a dominant role. For different pile-soil modulus ratio, the change of end resistance of piles had limited effect on the interaction factors of piles, thus the pile-soil modulus ratio had little effect on the interaction factors of piles.

3.4. Effects of pile spacing

The XCC pile group foundation was arranged squarely with 4 piles (2×2) and a pile spacing of 2.5 m in this section. The pile spacing was normalized by the outside diameter as the horizontal coordinate as shown in Fig. 9. When the load was less than 384 kN, the interaction factors of piles decreased with the increase of pile spacing. This was due to the reduction of the side friction, which played a controlling role to the interaction factors of piles at this situation. When the load was not less than 384 kN, the interaction factors firstly increased and then decreased with the increase of pile spacing.
4. Effect of raft on the bearing capacity of XCC piled raft foundation

The difference between pile group foundation and elevated pile foundation was whether there was a pile cap. As illustrated above, the pile cap of the XCC elevated pile foundation was regarded as a raft to study the effect of raft on the vertical bearing capacity of XCC piled raft foundation, and the properties of the cap were the same as those of raft of the XCC piled raft foundation. For convenience, a single XCC pile was considered as a pile group foundation with infinite pile spacing, and the load applied was 16 times that of a single pile foundation. Based on the above assumption, the difference between the XCC elevated pile foundation and XCC piled raft foundation was the raft of XCC piled raft foundation was in contact with the ground surface, and the cap of XCC elevated pile foundation had a certain distance from the ground surface. For controlling variables, the distance between the side pile and corresponding side of the raft or cap was equal to half of pile spacing.

Fig. 10 shows the settlement curve of XCC elevated pile foundation and single XCC pile foundation, in which letter “a” means the pile spacing. It could be found that the bearing capacity of XCC elevated pile foundation increased with the advancement of pile spacing, and was less than that of a single XCC pile. Settlement under the identical load was negatively correlated with pile spacing. One obvious reason for that was the interaction between piles decreased as the pile spacing increased, and this interaction had a negative influence on the bearing capacity of XCC elevated pile foundation. Another possible reason was that, if the raft was regarded as a kind of pile interaction, the interaction also decreased when the pile spacing increases. That was to say, the raft had a negative influence on the bearing capacity of XCC piled raft foundation as the interaction between piles compared with the foundation without rafts.

Figure 10. Settlement of elevated and single pile.
Fig. 11 shows the settlement of XCC elevated pile foundation and XCC piled raft foundation with pile spacing of 1.5 m and 2.1 m, in which letter “a” also means the pile spacing. When the load was less than 2000 kN, the settlement of XCC elevated pile foundation was smaller than which of XCC piled raft foundation for the same pile spacing and load, and the gap was narrow. That could be explained as this: the settlement of XCC piled raft foundation should be an intermediate value between the settlement when the load was fully borne by the pile body and the settlement when the load was fully borne by the soil, and the former was the settlement of XCC elevated pile foundation, the latter was far larger than that. When the load was less than 2000 kN, most of the load on XCC piled raft foundation was borne by pile body, which resulted that the settlement was greater but close to that of XCC elevated pile foundation.

With the increasing of load applied, the curve of XCC elevated pile foundation firstly appeared the steep drop section, and the settlement of XCC elevated pile foundation was greater than which of XCC piled raft foundation, the gap increased sharply as the load increased. If the abscissa values of the steep drop point in the curve was taken as the ultimate bearing capacity, the ultimate bearing capacity of XCC piled raft foundation was greater than that of XCC elevated pile foundation when the pile spacing is the same. And the ultimate bearing capacity of XCC elevated pile foundation with a pile spacing of 1.5 m was the minimum, which was 2640 kN. And that of XCC piled raft foundation with pile spacing of 2.1 m was the maximum, which was 3200 kN. The reason for this phenomenon might be as follows: when the load was large, the load of XCC elevated pile foundation was borne by pile body, the side friction had been fully developed at this time, and the extra load was mainly borne by end resistance. As for the XCC piled raft foundation, the side friction had not been fully developed because of the load sharing of raft. And the raft and pile could provide certain constraints on the soil between piles and strengthened it. Thus, the bearing capacity of XCC piled raft foundation was greater than that of XCC elevated pile foundation. It could also be found that pile spacing had greater effect on the bearing capacity of XCC piled raft foundation than that of XCC elevated pile foundation. This was due to the increase sensitivity of XCC piled raft foundation to pile spacing change.

5. Summary and conclusions

The finite element analysis of three-dimensional models established based on the field test of XCC pile foundation, the following conclusions can be obtained:

(a) Interaction factors of XCC piles decrease with the increasing load and the sensitivity of interaction factors to load change are negatively related to the distance from loaded pile. The interaction factors of XCC piles decrease as the pile number increases, and this trend gets more obvious with the decrease of load applied. The effect of pile number on the interaction factors of XCC piles was limited.
(b) The influence of pile-soil modulus ratio on the interaction factor of XCC piles is related to the load condition. When the load is small (less than 576kN), the interaction factors decrease with the increase of pile-soil modulus ratio, and when the load is larger, the interaction factors first increase and then decreases as the pile-soil modulus ratio increases, and the change range is small.

(c) When the load is small (less than 384 kN), the interaction factors of XCC piles are negatively correlated with the pile spacing, as the load increases (reached 384 kN), the interaction factors of XCC piles increase and then decrease when pile spacing increases. After approaching the ultimate load, the interaction factors of XCC piles will not change with the increase of pile spacing.

(d) The bearing capacity of XCC piled raft foundation is greater than that of XCC elevated pile foundation. The change of pile spacing has greater effect on the bearing capacity of XCC piled raft foundation than that of XCC elevated pile foundation because the interaction between raft and soil increases the sensitivity of XCC piled raft foundation to pile spacing change. The bearing capacity of XCC elevated pile foundation increases with the advancement of pile spacing. Settlement under the same load is negatively correlated with pile spacing.

(e) When the load is less than 2000 kN, the settlement of XCC elevated pile foundation is smaller than that of XCC piled raft foundation, and the gap is narrow. Most of the load on XCC piled raft foundation is borne by pile body and the settlement of XCC piled raft foundation is greater than that of XCC elevated pile foundation. With the increasing of load applied, the curve of XCC elevated pile foundation firstly appears the steep drop section, and the settlement of XCC elevated pile foundation is greater than that of XCC piled raft foundation, the gap increases sharply as the load increases.

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