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An Improvement of Bearing Capacity of Cement Mixing Pile Composite Foundation Considering Pile length

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Abstract. In view of the problem that the bearing capacity of cement mixing pile composite foundation is lower than that of undisturbed soil in the current code when the pile length is small. There are few theoretical or design studies on this issue in the existing literature. Using the theoretical analysis method, the main problems of the design calculation of cement mixing pile composite foundation in current codes are explained first. Based on the existing test results, the correlation between pile length and the bearing capacity of composite foundation and the coefficient β of soil bearing capacity between piles are analyzed. Combined with the pile length approaching 0m, two simple calculation methods of β are proposed. Finally, the rationality of each method is then analyzed based on actual engineering. The results show that β is equal to 1 when the pile length is 0m. When the pile length tends to 0m, β is slightly greater than 1, and it is only related to the displacement ratio and the exerting coefficient of pile tip resistance. Two methods for determining β with pile length are proposed. In case 1, there are declining, rising and stable sections for β with pile length. And in case 2, there are only decreasing and stable sections for β with pile length. The first case is more consistent with the reality, and can well deal with the situation of short pile length, such as the design and calculation of the bearing capacity of composite foundation when the bottom of the pit is strengthened. The research results have improved the bearing capacity theory of composite foundation with short length of cement mixed pile in current codes.

Keywords: road engineering; calculation improvement; theoretical analysis; cement mixing pile length; composite foundation; coefficient of soil bearing capacity between piles

1 Introduction

Cement mixing pile is widely used in composite foundation treatment and reinforcement of foundation pit in soft soil area. This kind of pile has remarkable effects in reducing soft foundation settlement and post-construction settlement, and can also effectively improve the bearing capacity of foundation[1-2]. Therefore, the design and

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calculation of cement mixing pile composite foundation is an important field in foundation treatment.

Cement mixing pile is a kind of flexible pile. In composite foundation, pile and soil between piles can play a better synergistic role[3-4]. In general, the bearing capacity of a cement mixing pile is controlled by the side resistance and the end resistance, and is also constrained by the strength of the pile. When pile length is small, pile side resistance is small, so pile side resistance and end resistance are the main controlling factors of single pile bearing capacity. When the pile length is longer, the sum of side resistance and end resistance of the pile is larger, and the pile strength becomes the main controlling factor[5-6]. This indicates that the bearing capacity of a single pile is related to the pile length. The research results of the existing literature also show that the bearing capacity of a single cement mixing pile cannot increase indefinitely with the pile length, and will gradually become stable. Therefore, cement mixing pile has an effective pile length[7-8]. The effective pile length is related to many factors such as foundation settlement, pile diameter, soil properties around pile and pile-soil modulus ratio[9]. However, the current codes do not consider the effective pile length in the design calculation.

The bearing capacity of cement mixing pile composite foundation is also related to pile length. Based on full scale test, Ma Hai-long and Chen Yun-min found that the bearing capacity of cement mixed pile composite foundation gradually increases and tends to be stable with pile length[10]. Similar results have been obtained in other literature[11]. According to current codes, when the bearing capacity of a single pile is controlled by the strength of the pile, the bearing capacity of composite foundation does not change with pile length, which is consistent with the research results of the above literature. In addition, the reinforcement of foundation pit and the treatment of pipeline foundation often use short pile cement mixing pile. Although the main function of pit bottom reinforcement is to improve anti-heave stability, the foundation treatment design of pit bottom often ignores the enhancement effect of pit bottom reinforcement soil on foundation bearing capacity, which will result in excessive foundation treatment. In a word, the research on the pile length and the bearing capacity of cement mixed pile composite foundation in the existing literature mainly focuses on the experiment, but the relevant theory or the calculation applicable to the actual design are rarely studied.

In this paper, the main problems concerning the design calculation of cement mixing pile composite foundation in current codes will be presented first. Based on the experimental results, the correlation between pile length and the bearing capacity of composite foundation and the coefficient of soil bearing capacity between piles is analyzed. Combined with the situation of pile length approaching 0m, two simple calculation methods of the coefficient of soil bearing capacity between piles are proposed. In these methods, the coefficient of soil bearing capacity between piles is affected by displacement ratio and pile length. Finally, the rationality of each calculation method is analyzed based on actual engineering, which provides a basis for the design and calculation of cement mixing pile composite foundation.

2 Existing Problem

According to ‘Technical Code for Ground Treatment of Buildings’ (Code: JGJ 79-2012) and ‘Technical Guidelines for Design and Construction of Highway Embankment and Soft Ground’ (Code: JTG/ TD31-02-2013), the bearing capacity characteristic value of cement mixing pile can be composed of two parts: pile side resistance and pile end resistance. At the same time, it should also meet the requirements of pile strength. That is, the characteristic value of bearing capacity of single pile is the smaller value of the two cases.

$$R_{\mathrm{a}} = u_{\mathrm{p}} \sum_{i=1}^{n} q_{\mathrm{ski}} l_{\mathrm{pi}} + \alpha q_{\mathrm{p}} A_{\mathrm{p}} \tag{1}$$

$$R_{\mathrm{a}} = \eta f_{\mathrm{cu,90d}} A_{\mathrm{p}} \tag{2}$$

Where, R_a (kN) is the characteristic value of the bearing capacity of a single pile; up (m) is the pile circumference. q_{ski} (kPa) is the characteristic value of lateral resistance of layer i soil around the pile. l_{pi} (m) is the thickness of layer i soil. α is the exerting coefficient of pile tip resistance. q_p (kPa) is the characteristic value of pile tip resistance. A_p (m^2) is the cross-sectional area of pile body. η is the reduction coefficient of pile strength. $f_{cu,\ 90d}$ (kPa) is the compressive strength of a 90d cube under standard curing conditions.

The bearing capacity of cement mixing pile composite foundation is:

$$f_{\mathrm{spk}} = \lambda m \frac{R_{\mathrm{a}}}{A_{\mathrm{p}}} + \beta \left(1 - m\right) f_{\mathrm{sk}} \tag{3}$$

Where, f_{spk} (kPa) is the characteristic value of bearing capacity of composite foundation. λ is the bearing capacity coefficient of a single pile, and the value of this coefficient is 1 when cement mixing pile is used. m is the replacement ratio. β is the coefficient of soil bearing capacity between piles. f_{sk} (kPa) is the characteristic value of soil bearing capacity between piles.

Assuming the diameter of cement mixing pile is 0.5m, the pile is arranged in a plum shape and the pile spacing is 1.2m, the displacement ratio can then be calculated as 0.1574. Soft soil is taken from a roadbed in Nansha, China. According to the geological survey report, the characteristic value of the bearing capacity of the foundation is 50kPa and the characteristic value of the lateral resistance is 12kPa. The $f_{cu,\ 90d}$ is 1.5MPa. Both α and β are 0.5. The relationship between pile length and bearing capacity of composite foundation is shown in Fig 1. Cement mixing pile can significantly improve the mechanical properties of soft soil, reduce foundation settlement and increase bearing capacity. However, when the pile length is less than about 1.9m, the bearing capacity characteristic value of composite foundation controlled by formulas (1) and (2) is lower than that of undisturbed soil.

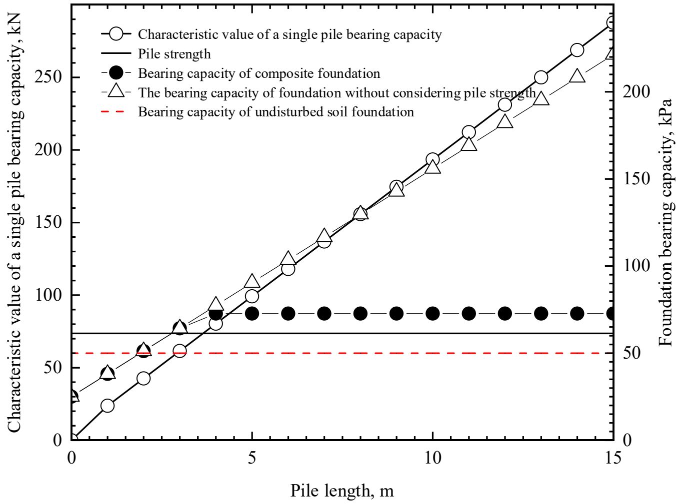

Fig. 1. Pile length VS bearing capacity characteristic value in cement mixing pile composite foundation

3 Calculation Improvement Considering Pile Length

3.1 The Pile Length

When the pile length varies, the variation rule of β can be obtained through tests. The field test results regarding the influence of the length of cement mixing piles on the bearing capacity of the silty clay composite foundation are presented in Fig. 2[10]. The pile diameter is 0.25m, the characteristic value of the pile side resistance is 8kPa, the bearing capacity of the undisturbed soil foundation is 60kPa, $f_{cu,\,90d}$ is 2.2MPa, and the displacement ratio is 0.196. The pile lengths are 3m, 5m, and 7m, respectively. The characteristic value of the bearing capacity of the composite foundation gradually increases with the pile length, but the rate of increase declines and the corresponding increment of the bearing capacity of the composite foundation also gradually decreases. The effective pile length of cement mixing piles has been widely confirmed. When the effective pile length exceeds a certain limit, the bearing capacity no longer increases significantly and eventually remains stable. Based on the bearing capacity of the composite foundation, the inverse calculated β value and its relationship with α and the pile length are shown in Fig. 3 and Fig. 4. As can be seen from the figures:

(1) When the pile length is 0m, that is, when there is no cement mixing pile treatment, the bearing capacity of the foundation should be equal to that of the untreated. So $\beta = 1$. When the pile length is 1m, β decreases with α. When the pile length is not less than 5m, the bearing capacity of a single pile is independent of α and only controlled by the pile strength, and β remains unchanged. When the pile length is 3m or 7m, the β is equal when the α is about 0.63, and the β is larger when the pile length is 3m before the intersection point.

(2) β gradually decreases and then increases with pile length, and reaches a minimum value of about 0.36 when the pile length is 5m. The fitting relationship between pile length and β in descending section and ascending section is shown in Table 1, where y represents β and x represents pile length. Both the descending and ascending sections show significant linear relationship. It should be noted that the test did not test larger pile lengths, and the β remained unchanged when the pile length was not less than 5m. Therefore, the ascending segment actually has only two data points, R^2 being 1. In fact, due to the existence of effective pile length, the characteristic value of bearing capacity of composite foundation will tend to a fixed value with pile length. Existing studies suggest that the effective pile length of cement mixed pile composite foundation is proportional to the square root of pile radius and pile-soil elastic modulus ratio. In soft soil area, the pile-soil elastic modulus ratio is about 50, and the effective pile length can be about 10m. When the bearing capacity of the cement mixed pile composite foundation is stable, the β is smaller than 1. And the pile length range of the rising section and the falling section is small, so it can be considered that the relationship between the rising section and the effective pile length is roughly linear.

It should be noted that when the bearing capacity determined by the strength of pile and pile side resistance/end resistance is equal, the corresponding pile length is about 4.3m, which is less than 5m in Fig. 4. Although the test data of 4.3m pile length is lacking, it can be seen from Fig. 2 that the increment of bearing capacity of composite foundation corresponding to 4.3m pile length is between 3m and 5m, indicating that the increment of bearing capacity of composite foundation is weakening and the declining section can still be regarded as a linear section.

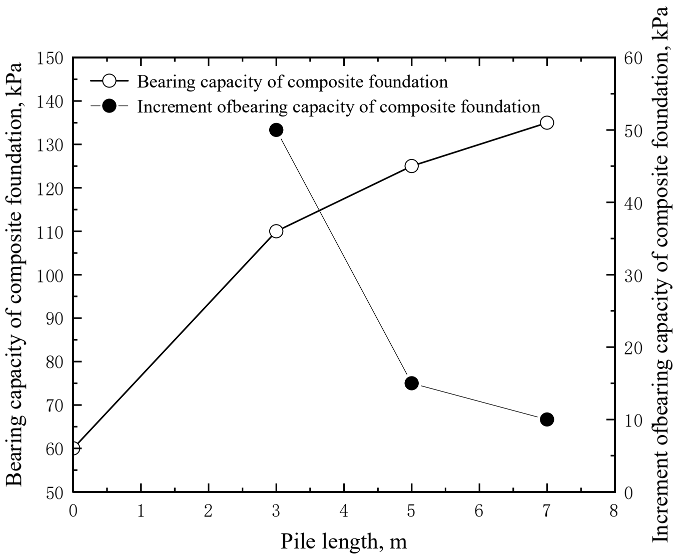

Fig. 2. Pile length VS bearing capacity of composite foundation

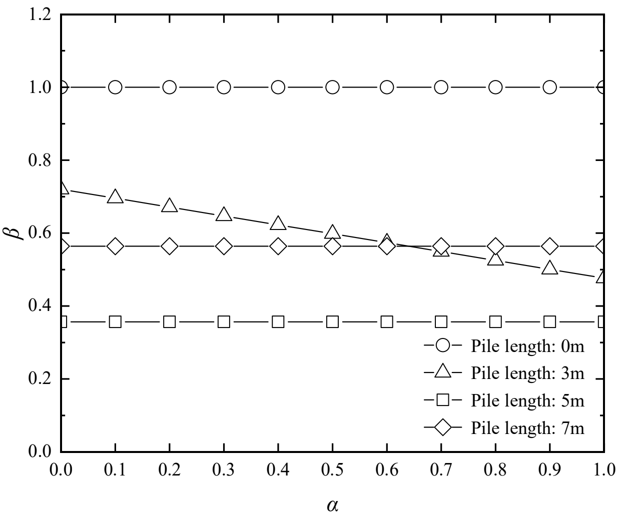

Fig. 3. α VS β

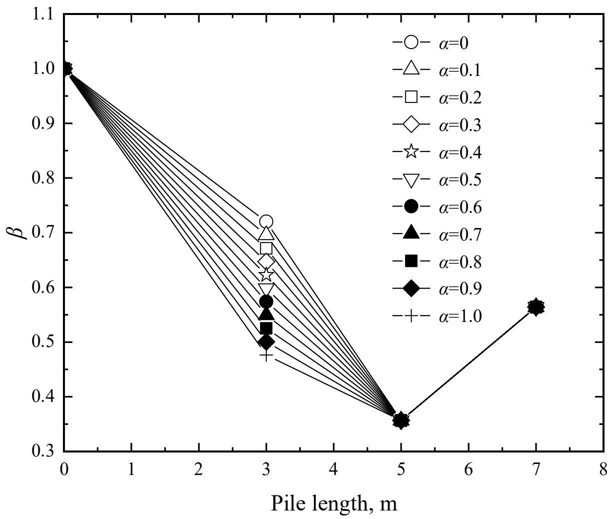

Fig. 4. Pile length VS β

Table 1. Summary of fitting formulas of pile length V β

Serial number	Section	α	Fitting equation	R^2
1	Descending section	0	y=-0.1259x+1.0279	0.9644
2		0.1	y=-0.1265x+1.0215	0.9788
3		0.2	y=-0.1272x+1.0151	0.9895
4		0.3	y=-0.1278x+1.0087	0.9965
5		0.4	y=-0.1285x+1.0023	0.9998

Serial number	Section	α	Fitting equation	R^2
6		0.5	y=-0.1291x+0.9959	0.9992
7		0.6	y=-0.1297x+0.9894	0.9951
8		0.7	y=-0.1304x+0.9830	0.9874
9		0.8	y=-0.1310x+0.9766	0.9767
10		0.9	y=-0.1317x+0.9702	0.9630
11		1.0	y=-0.1323x+0.9638	0.9468
12	Descending section as a whole	-	y=-0.1291x+0.9959	0.9719
13	Ascending section	-	y=0.1036x-0.1617	1

3.2 The Pile Length Approaches 0m

When the pile length is 0m, β=1. When the pile length approaches to but is not equal to 0m infinitely, β can be obtained by formula (4). The bearing capacity characteristic value of composite foundation is close to that of undisturbed soil, and the pile side resistance gradually decreases and then approaches 0kN, but the pile end resistance still exists. When pile length tends to 0m, β is only related to displacement rate and α. According to 'Technical Code for Ground Treatment of Buildings' (Code: JGJ 79-2012) and 'Technical Guidelines for Design and Construction of Highway Embankment and Soft Ground' (Code: JTG/ TD31-02-2013), α can be 0.4~0.6, and the middle value is then taken in this paper, that is, α=0.5. Both m and α are less than 1, and β obtained from formula (4) is then greater than 1.

$$\beta = \lim_{l\to 0}\frac{f_{\mathrm{spk}} - \lambda m\dfrac{R_{\mathrm{a}}}{A_{\mathrm{p}}}}{(1-m)f_{\mathrm{sk}}} = \lim_{l\to 0}\frac{f_{\mathrm{spk}} - \lambda m\dfrac{u_{\mathrm{p}}\sum_{i=1}^{n} q_{\mathrm{ski}} l_{\mathrm{pi}} + \alpha q_{\mathrm{p}} A_{\mathrm{p}}}{A_{\mathrm{p}}}}{(1-m)f_{\mathrm{sk}}}$$
$$= \lim_{l\to 0}\frac{f_{\mathrm{sk}} - \lambda m\alpha f_{\mathrm{sk}}}{(1-m)f_{\mathrm{sk}}} = \frac{1-m\alpha}{1-m} \tag{4}$$

3.3 Simplified Calculation Formula

When the bearing capacity determined by the strength of pile, pile side resistance/end resistance is equal, the corresponding pile length l_0 can be calculated by the following formula:

$$\sum_{i=1}^{n} q_{\mathrm{ski}} l_{\mathrm{pi}} = \frac{\eta f_{\mathrm{cu,90d}} A_{\mathrm{p}} - \alpha q_{\mathrm{p}} A_{\mathrm{p}}}{u_{\mathrm{p}}} \tag{5}$$

$$l_0 = \sum_{i=1}^{n} l_{\mathrm{pi}} \tag{6}$$

Based on the above analysis, this paper proposes the following two simplified calculation and determination methods for β:

(1) Case 1: there are descending and ascending sections of β with pile length

It can be seen from the above that the bearing capacity of the composite foundation without cement mixing pile treatment should be equal to that without treatment, that is, $\beta = 1$. When pile length approaches 0m, β is shown in formula (4). When the bearing capacity determined by the strength of pile, pile side resistance/end resistance is equal, β can reach a smaller value β_{min}. When the pile length is not less than the effective pile length, β should be the stable value β_{e}. See formula (7) for details:

$$\beta = \begin{cases} 1, & l = 0 \\ \dfrac{1 - m\alpha}{1 - m}, & l \to 0 \\ \beta_{\mathrm{min}}, & l = l_0 \\ \beta_{\mathrm{e}}, & l \geq l_{\mathrm{e}} \end{cases} \tag{7}$$

According to formula (5) ~ (7), the β value of any pile length can be then obtained:

$$\beta = \begin{cases} 1, & l = 0 \\ \dfrac{1 - m\alpha}{1 - m} - \left(\dfrac{1 - m\alpha}{1 - m} - \beta_{\mathrm{min}}\right)\dfrac{l}{l_0}, & 0 < l < l_0 \\ \beta_{\mathrm{min}} + \left(\beta_{\mathrm{e}} - \beta_{\mathrm{min}}\right)\dfrac{l - l_0}{l_{\mathrm{e}} - l_0}, & l_0 \leq l < l_{\mathrm{e}} \\ \beta_{\mathrm{e}}, & l \geq l_{\mathrm{e}} \end{cases} \tag{8}$$

It should be noted that in actual engineering, it is difficult to form a cement mixing pile when the pile length is larger than 20m, and the pile quality is also poor.

(2) Case 2: there is a descending section of β with pile length

Same as Case 1, when no cement mixing pile composite foundation treatment is carried out, β=1. When pile length approaches 0m, β is shown in formula (4). When there is a descending section, β is calculated by formulas (9) and (10). Obviously, Case 2 is simpler and easier to apply only in mathematical form.

$$\beta = \begin{cases} 1, & l = 0 \\ \dfrac{1 - m\alpha}{1 - m}, & l \to 0 \\ \beta_{\mathrm{e}}, & l \geq l_{\mathrm{e}} \end{cases} \tag{9}$$

$$\beta=\begin{cases}1, & l=0\\ \dfrac{1-m\alpha}{1-m}-\left(\dfrac{1-m\alpha}{1-m}-\beta_{\mathrm{e}}\right)\dfrac{l}{l_{\mathrm{e}}}, & 0<l<l_{\mathrm{e}}\\ \beta_{\mathrm{e}}, & l\geq l_{\mathrm{e}}\end{cases} \tag{10}$$

4 Difference Analysis

According to the pile test results in the Pearl River Delta region, for example, the vertical bearing capacity test of single pile and the bearing capacity test of composite foundation, when the pile length is greater than 10m, it can be considered that the β has reached a stable value. Based on engineering experience, the β with pile length in the Pearl River Delta region is finally stable in the range of 0.45~0.5, this paper suggests that β_e=0.45 as the stability value in this region and the β_{min} in this area is desirable 0.2.

Taking Wanhuan West Road of Nansha, Guangzhou as an example. The characteristic value of bearing capacity of single pile is 95kN. The characteristic value of bearing capacity of composite foundation is 120kPa. The pile length is 15m. The Pile diameter is 0.5m. The design value of 28d unconfined compressive strength is 0.8MPa. The thickness of cultivated soil and silty clay below the pile top is 7.2m and 7.8m, respectively. With the exception of the above two cases, it is assumed that β is always 0.45 (except for the pile length of 0m), which is named Case 3 in this paper.

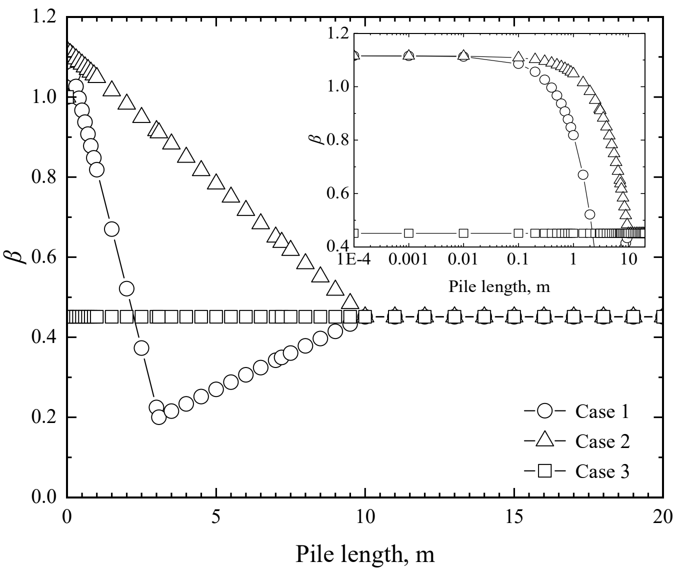

Fig. 5. β in three cases

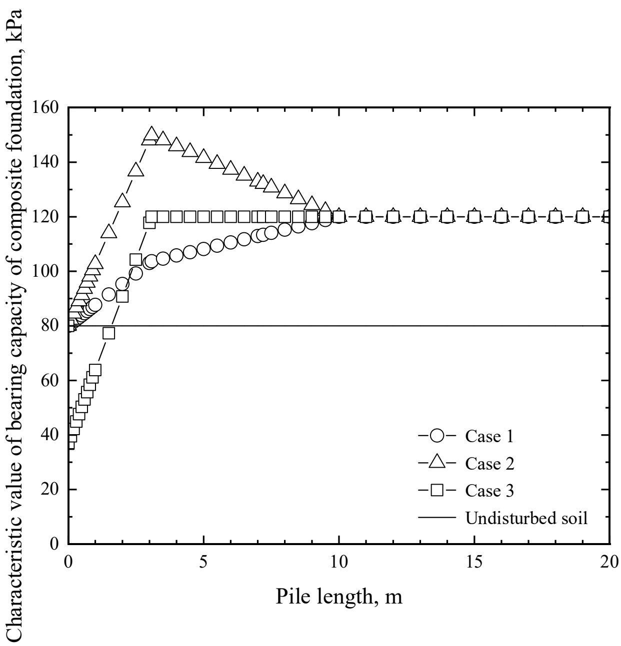

Fig. 6. Bearing capacity of composite foundation in three situations

When the bearing capacity of single pile controlled by pile strength and pile side/end resistance is equal, the corresponding pile length is 3.082m. The replacement ratio is 0.1874. When pile length approaches 0, β is 1.115. The bearing capacity characteristic values of β and composite foundation under these three cases are shown in Fig. 5 and Fig. 6, respectively. As can be seen from the figures:

(1) When the pile length is 0m, the β in Case 1 and Case 2 suddenly increases from 1 to 1.115, and then develops according to formula (8) and (10) respectively, and coincides with Case 3 when the pile length reaches 10m. In Case 3, when the pile length is 0m, β suddenly decreases from 1 to 0.45 and then remains unchanged.

(2) The characteristic value of bearing capacity of composite foundation in Case 1 gradually increases from 80kPa to 120kPa with pile length, and remains unchanged when pile length reaches 10m. In Case 2, the characteristic value of bearing capacity of composite foundation increases first, then decreases with pile length, and finally maintains a constant trend, reaching a peak value when the pile length is about 3m. In Case 3, when the pile length approaches 0m, the bearing capacity of the composite foundation suddenly decreases from 80kPa to about 36.8kPa, and increases with the pile length and reaches a stable value when the pile length is about 3m.

(3) When the pile length is 0m, the bearing capacity of the foundation in all three cases is 80kPa, which is consistent with the bearing capacity of the undisturbed soil. When the pile length reaches a certain degree, the bearing capacity of the composite foundation is the same under the three cases. The effective pile length of case 1 is 10m, while the effective pile length of Case 2 and 3 cannot be determined.

(4) In Case 2, the bearing capacity of composite foundation has a decreasing section with pile length, and an extreme value occurs when the pile length is small. In Case 3, when the pile length is small, the bearing capacity is smaller than that of undisturbed soil, and it reaches a stable value soon. Both cases are clearly inconsistent with reality.

(5) The length of cement mixing pile for pit reinforcement and pipeline foundation treatment is shorter. The calculation example demonstrates that even if the length of pile is shorter, it can still improve the bearing capacity of composite foundation. In practical engineering, the improvement of the reinforcement in the pit is often ignored, and the bearing capacity of the composite foundation is fully exerted by additional foundation treatment, which will lead to a large redundancy of foundation treatment design.

This shows that β varies with pile length rather than a fixed value, and Case 1 is more consistent with the reality and more reasonable, which can well deal with the situation of short pile length, such as the design and calculation of the bearing capacity of composite foundation when the bottom of the pit is strengthened. This improves the theory of bearing capacity of composite foundation with short length of cement mixing pile in current codes.

5 Conclusion

(1) According to the current norms, the bearing capacity of cement mixed pile composite foundation with smaller pile length is lower than that of undisturbed soil. Due to the presence of cement or other cementing materials, cement mixing piles should increase rather than reduce the bearing capacity of undisturbed soil. There are some defects in the calculation of bearing capacity of cement mixing pile composite foundation in the current codes, which is more obvious when the pile length is shorter.

(2) When the pile length is 0m, the bearing capacity of the foundation should be equal to that of the untreated, that is, β=1. When the pile length tends to be 0m, β is only related to the displacement ratio and α. And β is slightly greater than 1 in the range of common displacement ratio.

(3) Two methods for determining β with pile length are proposed. In case 1, there are descending, ascending and stable sections for β with pile length. In case 2, there are only descending and stable sections for β with pile length. When the cement mixing pile length is not less than the effective pile length, the stable value β_e can be calculated by the vertical bearing capacity test of single pile and the bearing capacity test of composite foundation.

(4) The pile test results show that Case 1 is more consistent with the reality, and β is related to the displacement ratio and pile length. This case can well deal with the situation of short pile length, such as the design and calculation of the bearing capacity of composite foundation when the bottom of the pit is strengthened. This improves the theory of bearing capacity of composite foundation with short length of cement mixing pile in current codes.

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