Research Article

Calculation Approach for Lateral Bearing Capacity of Single Precast Concrete Piles with Improved Soil Surrounds

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Precast concrete (PC) piles with cement-improved soil surrounds have been widely used for soft ground improvement. However, very few calculation approaches have been proposed to predict the lateral bearing capacity. This study aims at investigating the lateral capacity of a single PC pile reinforced with cement-improved soil through a series of 3D finite element analyses and theoretical studies. It is revealed that application of cement-improved soil around the PC pile can obviously reduce the induced lateral deflections and bending moments in the pile and can significantly increase its capacity to resist lateral loading. To account for the reinforcement effect of cement-treated soil, a modified m approach is proposed by introducing a modified coefficient to enable the predictions of the lateral bearing capacity for such reinforced PC piles. It is revealed that the modified coefficient is approximately linearly related to the compressive bearing capacity of improved soil surrounds.

1. Introduction

Deep cement-mixing (DCM) column has many advantages, such as a large volume, limited environmental disturbance, rapid construction, and low cost, so it is extensively used in soft ground improvement. However, the DCM column strength is significantly affected by soil conditions, which results in a low column uniformity and poor reinforcement effect [1]. Although a precast concrete (PC) pile has many advantages with various applications, the strength of the concrete pile cannot be sufficiently utilized under either vertical or lateral loading, and failure caused by soil failure can always occur, which makes it uneconomical for use in soft ground improvement [2]. To solve the abovementioned problems, the PC pile with improved soil surrounds, produced by inserting a PC pile into a DCM column before the initial setting of cement-improved soil (Figure 1), has recently been proposed [1, 2]. In this way, the high-strength PC pile is designed to bear a load, and the improved soil surrounds act to transfer axial force into the surrounding soils by skin frictions [2]. To date, this new type of composite pile has attracted considerable attention owing to its low cost

and high effectiveness and has been successfully applied to soft ground improvement [3–5].

To investigate the vertical bearing characteristics of PC piles with improved soil surrounds, a series of pile load tests, numerical simulations, and theoretical models have been carried out [5–9]. These studies verified that the application of cement-improved soil surrounds could greatly improve the vertical bearing capacity of the PC pile and reduce its settlement. However, further studies are also needed to evaluate the contribution of improved soil surrounds to the lateral performance of PC piles. Liu [10] performed full-scale lateral load tests on several PC piles with improved soil surrounds. The test results showed that owing to the presence of outer improved soil surrounds, the lateral bearing capacity and the lateral stiffness of the PC piles are significantly increased. Rollins et al. [11] performed lateral loading tests on an existing pile group modified with jet-grouting and cement-mixing column reinforcement around the pile caps. It was observed that the lateral resistance of the existing pile group foundations could be significantly increased with jet-grouting and cement-mixing reinforcement. Based on the field tests of Rollins et al. [11], Lin et al. [12] used the finite

FIGURE 1: (a) Schematic diagram of PC pile with improved soil surround; (b) photo of field excavation.

difference simulation method to model the laterally loaded pile groups in soft clay with or without the jet-grouting columns. In addition, Wang et al. [13] and He et al. [14] carried out monotonic and cyclic lateral loading tests to investigate the contributions of the jet-grouting column reinforcement to improve the lateral performance of the single cast-in-place pile.

Although field observations and numerical modeling of laterally loaded piles with jet-grouting or cement-mixing column reinforcement have been reported, systematic studies pertaining to the contributions of cement-treated soil surrounds to the lateral capacity of PC piles are still somewhat lacking. Indeed, there is still much that is not well understood about the lateral capacity of PC piles with such improved soil surrounds. In addition, there has generally been a limited amount of theoretical studies pertaining to the lateral bearing capacity of single PC piles with improved soil surrounds, so this requires further investigation.

This paper aims at conducting a comprehensive study on the lateral response of PC piles with improved soil surrounds as well as the m approach for predicting the bearing capacity under lateral loading. To achieve the research objectives, three-dimensional (3D) numerical analyses that were first validated against field test results were performed using Midas/GTS finite element software. The effect of outer improved soil surrounds on the lateral response of PC piles was further assessed. Moreover, a modified m approach accounting for the cement-improved soil reinforcement was proposed for the reinforced piles within the cohesive soil, and the suitability of the proposed m approach for predicting the lateral bearing capacity of such reinforced piles was also assessed.

2. Numerical Simulations

In order to evaluate the effect of cement-improved soil surrounds on the lateral bearing performance of a PC pile, the Midas/GTS software was used to establish three-dimensional models of PC piles with and without improved soil surrounds under lateral loading, according to

the full-scale pile load tests. The test project was performed in Nantong, which is located along the southeast coast of China. Extensive field tests and laboratory tests were performed to characterize the subsoil conditions. Specifically, conventional laboratory soil tests were carried out to determine the unit weight, compression modulus, and relevant shear parameters of the soil mass. Moreover, a cone penetration test (CPT), which is one of the most commonly used field test approaches in geotechnical investigations, was performed to determine the ultimate unit skin friction and tip resistance. The soil profile and engineering properties of the test site are presented in Figure 2. It can be seen that the soil profile near the ground surface consists of a marine silty clay layer underlain by a silty sand deposit. The deflection and bending moment distribution of the two types of piles are then investigated in detail. The detailed information of the test piles is shown in Table 1.

2.1. Numerical Modeling. In general, there are different numerical approaches for analysis of the lateral bearing capacity of a single pile [15]. One approach is to establish the pile-soil model based on the lateral pile-soil interaction. The other is to establish the pile-spring model by replacing the pile-surrounding soil with equivalent spring and damping based on the Winkler elastic foundation beam theory. Although the pile-spring model can simulate the compressive and nontensile behavior of pile-surrounding soil, it cannot reflect the plasticity of pile-surrounding soil. It is well known that with a gradual increase in the lateral load applied at the pile head, the pile-surrounding soil changes from behaving elastically to plastically, and the plastic zone around the pile is gradually extended. In addition, in the pile-spring model, the size of the pile-soil contact surface is assumed to be constant under different loading conditions. In the pile-soil model, however, the contact surface may change with varying loading conditions, which is more consistent with the actual pile-soil interaction. Therefore, the pile-soil model was adopted in this study.

FIGURE 2: Soil profile and engineering properties of the test site.

TABLE 1: Detailed information about test piles (PCI-1 and PC-1).

Pile identifier	Concrete grade	PC piles			Improved soil surrounds	
		Outer diameter (mm)	Wall thickness (mm)	Length (m)	Outer diameter (mm)	Length (m)
PCI-1	C80	400	95	12	800	12
PC-1	C80	400	95	12	—	—

Note. PCI = PC pile with improved soil surround; PC = PC pile without improved soil surround.

The typical 3D finite element models used for the analyses are shown in Figures 3(a) and 3(b). In the horizontal direction, the surrounding soil was extended by 10 times greater than the pile diameter. Meanwhile, in the vertical direction, the surrounding soil was the same length as the pile. The soil and pile were modeled using 3D eight-node linear brick elements, with a refined mesh of 33,600 elements. Particularly, the mesh used for the soil was sufficiently fine in the region close to the pile. Regarding the meshing convergence issue, a numerical test shows that further halving the current mesh size can only result in a change of numerical results of no more than 0.6%. This suggests that sufficiently accurate simulation results can be achieved with the mesh size adopted in this study.

A total stress analysis under undrained conditions was adopted in this study to simulate the field lateral load tests on the PC pile with improved soil surround, which did not account for the pore water pressure response. Such a modeling technique has been used by many scholars [16–20] in investigations of the behavior of a single pile subjected to lateral loading. Accordingly, the total stress parameters for both the undrained modulus and shear strength of the cement-treated and untreated soil were assigned in this numerical study. The Mohr–Coulomb failure criterion was adopted to compute the failure loads of pile-surrounding soils deforming under undrained conditions. The undrained shear strength $C_u = 20$ kPa and undrained Young's modulus $E_u = 750C_u$ for the silty clay were then determined through the undrained shear tests and the work of He et al. [20], respectively. The cement-treated soil was also assumed to

obey the Mohr–Coulomb failure criterion. Specifically, the undrained shear strength and Young's modulus of the cement-treated soil were obtained from the work of Jamsawang et al. [21] and Tyagi et al. [22]. According to Jamsawang et al. [23], the tensile strength (σ_t) of cement-treated soil can be defined as 0.15 times the compressive strength. The constitutive models and parameters used in this study are listed in Table 2. It is worth noting that the cement-improved soil is considered as homogeneous without varying with depth.

The interaction between the PC pile and the improved soil surrounds was modeled by defining zero-thickness interface bond-slip elements at their contact surfaces, so as to allow for the relative shear displacement between, and the separation of the two objects. The interface cohesion and friction coefficient between the pile and cement-treated soil were derived as 200 kPa and 0.65, respectively. Considering that slippage and gapping occurs during lateral loading, the interaction between the cement-improved soil and the surrounding soil was modeled using the Coulomb friction model. An interface friction coefficient of 0.35 was applied in this study. The finite element analyses were comprised of two primary steps. First, the initial stress field of the pile-soil system was balanced. In the next step, lateral loads were applied at the pile head by multiple-step loading.

2.2. Validation and Results. Figure 4 compares the measured and computed lateral load (P) versus the deflection (Y_0) curve at the head of the piles with and without improved soil

FIGURE 3: 3D finite element models of (a) entire pile-soil system and (b) pile with improved soil surround.

TABLE 2: Material models and parameters used in this study.

Material type	Model	γ (kg/m ³)	E_u (MPa)	ν	C_u (kPa)	Φ (°)	σ_t (kPa)
Shallow silty clay	Mohr-Coulomb	1780	15	0.49	20	—	—
Deep silty sand	Mohr-Coulomb	1920	35	0.49	—	30	—
Cement-improved soil	Mohr-Coulomb	2100	300	0.49	450	—	300
PC pile	Linear elastic	2400	38000	0.20	—	—	—

surrounds, respectively. It can be seen that the computed pile-head deflections agreed well with the numerical results in the case of a lateral load less than 100 kN. However, when the lateral load exceeded 100 kN, the computed results were significantly different from the corresponding measured values. For laterally loaded flexible piles, failure of the pile-soil system can always be a result of the plastic damage of the pile following yielding of the pile-surrounding soil [20, 24]. Additionally, the lateral bearing capacities of these two types of piles were determined to be 125 kN and 95 kN, respectively, according to *Technical Code for Building Pile Foundations* [25]. Therefore, in this study, once the lateral load was applied up to 100 kN, the severe tension-induced damage in the pile occurred and its flexural rigidity obviously decreased, resulting in a steep increase in the pile deflection. However, the numerical modeling does not take the pile damage into account, which leads to the foregoing difference. It is worth mentioning that the lateral bearing capacity of the PC

pile with cement-treated soil reinforcement was approximately 30% larger than that of the unreinforced PC pile, which indicates an essential strengthening effect with the application of cement-improved soil around a PC pile.

Figure 5 shows the computed lateral deflection along the PC pile with and without improved soil surrounds in the case of a lateral load of 100 kN. It can be observed that both types of piles behaved as flexible piles, and the pile deflection decreased nonlinearly from the pile head, with the deflection primarily distributed at the upper part of the pile body. This suggests that the shallow soil layer, which ranged from 0 m to approximately 5 m below the ground surface, played a key role in the bearing performance of the PC pile subjected to lateral loading. A comparison indicates that the lateral deflection along the PC pile with improved soil surrounds was obviously smaller than that of the PC pile alone in the soil. This is because the pile deflection at a certain depth was closely related to the pile-soil modulus ratio. When a PC pile

FIGURE 4: Comparisons between the measured and computed P - Y_0 curves for pile PCI-1 and pile PC-1.

FIGURE 5: Computed lateral deflection along pile PCI-1 and pile PC-1 at a lateral load of 100 kN.

was concentrically inserted into the cement-improved soil surrounds, the greater constraint effect provided by the outer cement-improved soil undoubtedly caused a noticeable decrease in pile deflection.

FIGURE 6: Computed bending moment along pile PCI-1 and pile PC-1 at a lateral load of 100 kN.

Figure 6 shows the computed bending moment along the PC piles with and without improved soil surrounds in the case of a lateral load of 100 kN. It is evident that the variations in the bending moment along the PC pile with improved soil surrounds were consistent with that along the PC pile alone in soil. To be specific, the bending moment increased monotonically to a peak and then gradually decreased, which had also been reported by Liu [10]. It is clearly observed that the maximum bending moment of the PC pile with improved soil surrounds was significantly smaller than that of the PC pile alone in soil. This can be attributed to the fact that the presence of the improved soil surrounds resulted in a large equivalent diameter of the pile, which could generate greater soil resistance to the pile deflection, thus significantly reducing the bending moment in the PC pile. The reduction is also in agreement with Voottipruex et al. [6] and Liu [10], who found that the outer improved soil surrounds may play a critical role in load transfer and can effectively transfer the lateral load from the PC pile to the surrounding soil.

Although the application of cement-improved soil around a PC pile could greatly reduce the accumulation of pile deflection and bending moment, both types of piles experienced similar trends when subjected to lateral

TABLE 3: Value of proportional coefficient m of soil lateral resistance coefficient (JGJ 94-2008).

Type of foundation soil	m (kN/m ⁴)	PC piles
		Corresponding lateral deflection of a single pile at ground surface (mm)
Muck and muddy soil, saturated collapsible loess	2000~4500	10
Liquefied plastic ($I_L > 1$), soft plastic ($0.75 < I_L \leq 1$) clayey soil, $e > 0.9$ silty soil, loose silty fine sand, loose and slightly dense fill	4500~6000	10
Plastic ($0.25 < I_L \leq 0.75$) clayey soil, $e = 0.75 \sim 0.9$ silty soil, collapsible loess, medium dense fill, slightly dense fine sand	6000~10000	10
Hard plastic ($0 < I_L \leq 0.25$) and hard ($I_L \leq 0$) clayey soil, collapsible loess, $e < 0.75$ dense silty soil, medium dense medium sand, dense old fill	10000~22000	10

loading. This suggests that the lateral bearing behavior of the PC pile with improved soil surrounds was similar to that of the PC pile alone in soil. Therefore, the m approach applicable to a single PC pile without improved soil surrounds can still be used to calculate the lateral bearing capacity of a single PC pile with improved soil surrounds. But related parameters in the existing m approach need to be modified so as to reflect the reinforcement effect of improved soil surrounds on the lateral bearing performance of PC piles.

3. Modified m Approach for PC Piles with Improved Soil Surrounds

3.1. m Approach. The m approach was proposed based on the Winkler elastic foundation model and Euler–Bernoulli beam theory, and it is assumed that the lateral soil resistance at a certain depth equals the product of the corresponding lateral resistance coefficient and pile deflection. Moreover, the lateral resistance coefficient linearly increases with the depth and is equal to zero at the ground surface.

According to the *Technical Code for Building Pile Foundations* [25], the calculation formula for the lateral bearing capacity of a single PC pile is expressed as

$$R_{ha} = \beta \frac{\alpha^3 EI}{v_x} \chi_{0a}, \quad (1)$$

where R_{ha} = design value of the lateral bearing capacity of single PC piles (kN); β = reduction coefficient, generally taken as 1.0; χ_{0a} = allowable lateral deflection at pile head (m); v_x = pile-head deflection coefficient; EI = flexural stiffness of pile (kN·m²); and α = lateral deformation coefficient of pile, which is given as

$$\alpha = \sqrt[5]{\frac{mb_1}{EI}}, \quad (2)$$

where b_1 = calculation width of pile (m) and m = proportional coefficient of lateral resistance coefficient (kN/m⁴), which can be determined by the *Technical Code for Building Pile Foundations* [25], as summarized in Table 3.

It should be noted that for the PC piles with improved soil surrounds, the flexural stiffness and tensile strength of

the outer cement-improved soil are significantly lower than that of the inner PC pile, and severe cracking in cement-improved soil can be easily induced under lateral loading. In other words, slippage and separation is likely to occur at the interface of the PC pile and the cement-improved soil during loading. Thus, the two parts of the reinforced piles cannot work together to support and transfer the lateral load effectively, especially in cases of cement-improved soil with low strength. Based on the above analysis, it is reasonable to treat the outer improved soil surrounds as the pile-surrounding soil with greater soil resistance, rather than as the extended diameter of a PC pile. As a result, the parameters EI and b_1 of the PC pile were used to predict the lateral bearing capacity of a PC pile with improved soil surrounds.

It is well known that the proportional coefficient, m , is a key parameter for analysis of laterally loaded piles when using the m approach. However, the m value is closely dependent on soil properties, pile material, loading conditions, and so on [26]. Hence, in order to determine the m value applicable to PC piles with improved soil surrounds, it is required to consider the reinforcement effect of improved soil surrounds on the lateral PC pile.

3.2. Back-Calculation of m Value. In cases of the lateral load on the free-head pile is applied at the ground surface, the coefficient, m , is determined from (1) and (2) as follows:

$$m = \frac{(v_x P)^{5/3}}{b_1 Y_0^{5/3} (EI)^{2/3}}, \quad (3)$$

where P and Y_0 = lateral load (kN) and pile-head deflection (m), corresponding to R_{ha} and χ_{0a} , respectively.

From (3), it can be seen that the variation of m with Y_0 can be deduced according to the P - Y_0 curve derived from pile load tests. In general, at a pile-head deflection of 10 mm, the applied load, P , is defined as the design value of lateral bearing capacity of single piles. As a result, the m value used to determine the lateral bearing capacity of single piles can be obtained from the m - Y_0 curve.

Figure 7 shows the deduced m - Y_0 curves for single PC piles with and without improved soil surrounds based on

FIGURE 7: Deduced m - Y_0 curves for lateral test piles.

TABLE 4: Detailed information of test piles (PCI-2~PCI-4; PCI-L1~PCI-L8).

Pile identifier	Concrete grade	PC piles			Improved soil surrounds	
		Outer diameter/edge length (mm)	Wall thickness (mm)	Length (m)	Outer diameter (mm)	Length (m)
PCI-2	C80	400	95	12	800	15
PCI-3	C80	600	110	9	800	9
PCI-4	C80	600	110	9	800	9
PCI-L1, L2*	C35	220	—	6	600	7
PCI-L3, L4*	C35	220	—	4	600	7
PCI-L5, L6*	C35	180	—	6	600	7
PCI-L7, L8*	C35	180	—	4	600	7

*Note. PCI-L1~PCI-L8 are solid square PC piles with improved soil surrounds reported by Jamsawang et al. [4].

the results of pile load tests, which were conducted in Nantong, China, and reported by Jamsawang et al. [4]. The detailed information of such test piles is summarized in Tables 1 and 4. Generally, under large deflection levels, the m value gradually decreased with the increasing deflection. At a pile-head deflection of 10 mm, the back-calculated and recommended m values (shown in Figure 7 and Table 3, resp.) are compared in Table 5. From these results, it is clearly demonstrated that the back-calculated m value for the PC pile without improved soil surrounds was very close to the recommended m value. However, the back-calculated m values for PC piles with improved soil surrounds were 1.6 to 5.0 times larger than the recommended values for PC piles alone in soil. This denotes that

the improved soil surrounds led to an obvious increase in the m values of the PC piles.

3.3. Modified Coefficient. In order to clearly distinguish the significant difference between the back-calculated and recommended m values, a modified coefficient, ξ_m , is defined as follows:

$$\xi_m = \frac{\text{the back-calculated } m \text{ value}}{\text{the recommended } m \text{ value (maximum)}} \quad (4)$$

Table 6 shows the modified coefficients for different test piles and several parameters of outer improved soil surrounds. It can be seen from Table 6 that the strength of

TABLE 5: Back-calculated and recommended m values at a pile-head deflection of 10 mm.

Pile identifier	Type of foundation soil	Back-calculated m value (kN/m ⁴)	Recommended m value (kN/m ⁴)
PCI-1	Silty clay, silty sand	50000	6000~10000
PC-1		11000	6000~10000
PCI-2	Silty soil, silty sand	25000	6000~10000
PCI-3		16000	6000~10000
PCI-4		35000	6000~10000
PCI-L1		15000	4500~6000
PCI-L2	Weathered soil, soft soil	14400	4500~6000
PCI-L3		14400	4500~6000
PCI-L4		14400	4500~6000
PCI-L5		18000	4500~6000
PCI-L6		17400	4500~6000
PCI-L7		17400	4500~6000
PCI-L8		16800	4500~6000

TABLE 6: Modified coefficients for different test piles and several parameters of outer improved soil surrounds.

Pile identifier	Improved soil surrounds			Modified coefficient ξ_m
	Cross-sectional area (m ²)	Compressive strength (MPa)	Compressive bearing capacity (kN)	
PCI-1	0.3768	2.00	753.6 (dry spraying)	5.0
PCI-2	0.3768	0.77	290.1 (wet spraying)	2.5
PCI-3	0.2198	0.60	131.9 (wet spraying)	1.6
PCI-4	0.4067	1.20	488.0 (dry-wet spraying)	3.5
PCI-L1	0.2342	0.94	219.5 (wet spraying)	2.5
PCI-L2	0.2342	0.91	212.7 (wet spraying)	2.4
PCI-L3	0.2342	0.88	205.8 (wet spraying)	2.4
PCI-L4	0.2342	0.88	205.8 (wet spraying)	2.4
PCI-L5	0.2502	0.93	233.6 (wet spraying)	3.0
PCI-L6	0.2502	0.90	225.3 (wet spraying)	2.9
PCI-L7	0.2502	0.90	225.3 (wet spraying)	2.9
PCI-L8	0.2502	0.87	217.0 (wet spraying)	2.8

FIGURE 8: Correlation between the modified coefficient and compressive bearing capacity of improved soil surrounds.

cement-treated soil with the wet spraying method was generally lower than that with the dry spraying method. It is known that the improvement of the soil with cement treatment is referred to as the chemical reactions between cement and the soil particles, and the water-cement ratio has an important influence on the mechanical properties

of cement-treated soil. Once the water-cement ratio exceeds the optimum level, the strength of cement-treated soil obviously decreases with the increasing water-cement ratio [27, 28]. It is worth noting that, in practical engineering, the initial water content of the natural clay undoubtedly increases the water-cement ratio of the cement-treated soil. Thus, it can be concluded that the lower strength of a DCM column can always occur when constructed using the wet spraying method, especially in coastal areas with a high groundwater level and water content.

It can be observed that the m value for PC piles with improved soil surrounds was not only dependent on soil properties but also closely related to the compressive strength and cross-sectional area of outer improved soil surrounds. The larger the cross-sectional area and the higher the compressive strength of the improved soil surrounds, the larger the modified coefficient. This can be attributed to the different reinforcement effects of outer improved soil surrounds. Fortunately, the reinforcement effect of outer improved soil surrounds was found to be positively related to its compressive bearing capacity (denoted as Q_u (kN)). Thus, a correlation relationship between ξ_m and Q_u can be established. As shown in Figure 8, for PC piles with improved soil surrounds, ξ_m exhibited an

FIGURE 9: Comparison of lateral bearing capacity using the modified and existing m approach and measured results.

approximately linear increase with Q_u . Moreover, when $Q_u = 0$ (corresponding to the PC pile without improved soil surrounds), the modified coefficient, ξ_m , should be determined as 1.0. Thus, the linear correlation function is fitted as follows:

$$\xi_m = 0.0056Q_u + 1. \quad (5)$$

In summary, for laterally loaded single PC piles with improved soil surrounds, the m value can be obtained by introducing the modified coefficient. Thus, a modified m approach is proposed by modifying the m value based on the existing m approach, that is, by substituting the modified m value into the existing equation. The proposed m approach can account for the cement-treated soil reinforcement.

4. Evaluation of the Modified and Existing m Approach for Piles with Improved Soil Surrounds

According to the pile load test data presented in this study, the lateral bearing capacities of these test piles were calculated using the modified and existing m approach, as shown in Figure 9. It is clearly seen that the lateral bearing capacities obtained by the modified m approach were all in good agreement with the measured results, with a relative error range of 15%. These results also indicate that the modified m approach was able to effectively account for the reinforcement effect of outer improved soil surrounds. Therefore, it is feasible and appropriate to predict the lateral bearing capacity of PC piles with improved soil surrounds by using the modified m approach. However, the calculated bearing capacities from the existing m approach were obviously smaller than that measured, indicating that the

existing m approach would significantly underestimate the lateral capacity of such reinforced piles. This implies that designs of laterally loaded single PC piles with improved soil surrounds using the existing m approach would tend to be conservative.

To further assess the suitability of the modified m approach for the analysis of laterally loaded piles with improved soil surrounds, the deflection and moment responses derived using the modified and existing m approach were compared with the numerical results (from Figures 5 and 6), as demonstrated in Figures 10 and 11, respectively. It is evident that both the pile deflection and moment from the existing m approach were significantly larger than those from the numerical results. However, compared with the numerical results, the modified m approach can accurately predict the lateral response of a reinforced PC pile. This also further indicates that the proposed m approach is applicable for laterally loaded single PC piles with improved soil surrounds and would be especially useful in practice.

5. Conclusions

In this paper, the numerical and theoretical investigation on the lateral bearing capacity of a single PC pile with improved soil surrounds was presented. The existing m approach (recommended by Technical Code for Building Pile Foundations (JGJ 94-2008)) was modified by taking into account the reinforcement effect of outer improved soil surrounds. The primary conclusions that can be obtained from this study are summarized below:

- (1) By applying cement-improved soil around a PC pile, the lateral deflection and the maximum bending moment of the PC pile are significantly reduced.

FIGURE 10: Comparison of predicted pile deflections from the modified and existing m approach and numerical results at a lateral load of 100 kN.

FIGURE 11: Comparison of predicted pile moments from the modified and existing m approach and numerical results at a lateral load of 100 kN.

Nevertheless, the lateral performance of the PC pile with improved soil surrounds is similar to that of the PC pile alone in soil. Thus, the lateral bearing capacity of a single PC pile with improved soil surrounds can still be calculated using the m approach.

- (2) To account for the reinforcement effect of improved soil surrounds on the laterally loaded single PC piles, a modified m approach was proposed by introducing a modified coefficient based on the existing m value. The modified coefficient, ξ_m , is approximately linearly related to the compressive bearing capacity of cement-improved soil surrounds.
- (3) Compared with numerical results, the proposed m approach can accurately predict the lateral bearing capacity of single PC piles with improved soil surrounds. In addition, the existing m approach obviously underestimates the lateral bearing capacity of such reinforced PC piles, thus leading to a conservative prediction of their lateral performance.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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