Hindawi
Advances in Civil Engineering
Volume 2023, Article ID 5552990, 10 pages
https://doi.org/10.1155/2023/5552990

Research Article

Experimental Study on Bonding Performance between Prestressed Concrete Pipe Piles and Core Grout

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Received 18 May 2023; Revised 23 July 2023; Accepted 22 August 2023; Published 11 September 2023

Academic Editor: Paul Awoyera

To make the bearing capacity tests safer and more affordable for prestressed high-strength concrete (PHC) piles, this paper proposes a reaction device for anchor piles filled with core grout based on the geometric and mechanical characteristics of PHC piles. The proposed reaction device has the advantages of convenient construction, strong controllability of the connection quality and low cost. In addition, the pile will not experience prestress unloading or tensile stress under the effect of the upward pulling load. To promote the application of the reaction device developed for PHC pile bearing capacity tests, experimental studies are conducted on the bonding performance between the core grout and the inner wall of the PHC pile. The influence of various factors such as the strength of the core grout, the grouting length, the curing time, and the inner diameter of the PHC pile on the bond strength between the core grout and the inner wall of the PHC pile are investigated. Results show that as the inner diameter of the PHC pile increases, the bond strength between the core grout and the inner wall of the PHC pile decreases with a maximum difference of 5%. The bond strength decreases as the grouting length increases, and gradually stabilizes, with a difference of no more than 10% between the maximum and minimum bond strength values. The higher the strength of the grout is, the greater the bond strength between the core grout and the inner wall of the PHC pile is. The bond strength between the core grout and the inner wall of the PHC pile increases with the increase of the curing time within 28 days of curing, and the bond strength at 3 days meets the requirements of the PHC pile bearing capacity test.

1. Introduction

Static load test methods can intuitively display the mechanical behaviors of tested piles and are considered to be the most reliable and accurate for determining the bearing capacity of a single pile [1, 2]. The reaction devices used in static load test methods include the load-bearing platform reaction devices, the anchor pile reaction devices, and so forth [3]. The load-bearing platform reaction devices are widely used in static load testing. However, heavy objects, which are required to be stacked on the support piers on both sides of the tested pile at once, requires high energy consumption and high labor costs during transportation and hoisting. In addition, static load tests may fail or even cause accidents due to insufficient bearing capacity or stiffness [4]. Therefore, anchor pile reaction devices are generally recommended by technical specifications for bearing capacity testing of foundation piles [3, 5, 6].

Due to the advantages of low cost, high bearing capacity of a single pile and good reliability, prestressed high-strength concrete pipe piles (referred to as PHC pipe piles) have been widely used in foundation engineering [7–9]. In a PHC pipe pile, the longitudinal steel bars do not extend out of the pile top, which makes it impossible to directly connect the pile with the reaction beam. This limits the application of anchor pile reaction devices in the bearing capacity testing of PHC pipe piles. To address this issue, engineers developed the clamping connection method and the core concrete connection method [10–13].

In the clamping connection method, a specially designed mechanical connection is used, with bolt holes on the side matched with high-strength bolts (as shown in Figure 1(a)). When the clamping connection method is used, the uplift

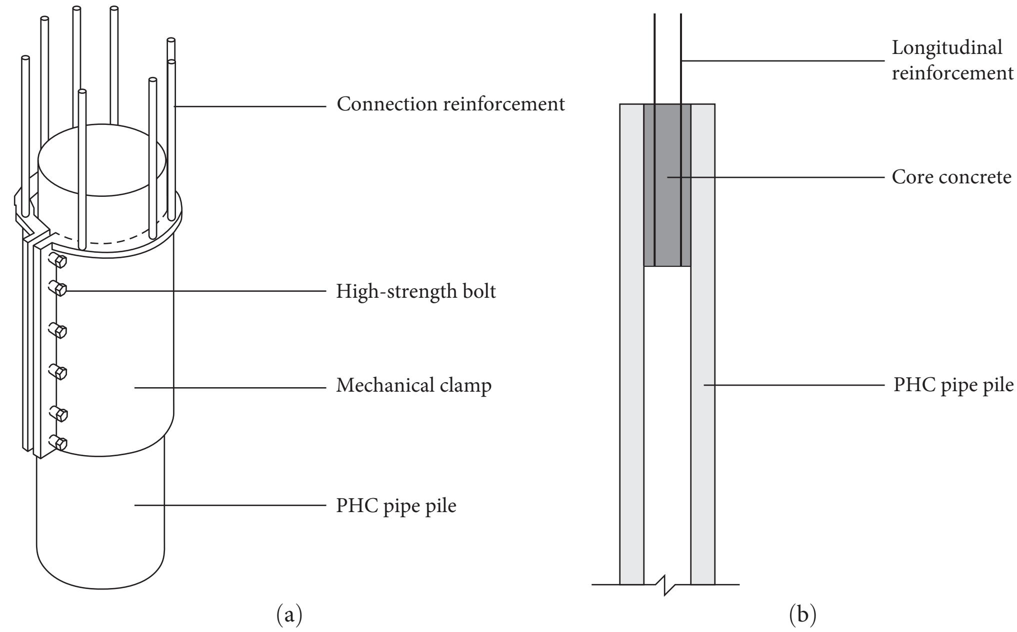

FIGURE 1: Application of the anchor pile reaction device in PHC pipe pile bearing capacity testing. (a) The clamping method and (b) the core concrete method.

load borne by the anchor pile is transmitted through the longitudinal force between the clamp mechanical connection and the PHC pipe pile [11]. The longitudinal force includes the mechanical interlocking effect and the longitudinal frictional force between the clamp mechanical connection and the PHC pipe pile, and the magnitude of the longitudinal force depends on the pressure of the clamp mechanical connection acting on the radial direction of the PHC pipe pile. When the pressure of the clamp mechanical connection acting on the radial direction of the PHC pipe pile is too large, longitudinal cracks occur in the PHC pipe pile under the radial pressure, which has an adverse effect on the durability of the PHC pipe pile. When the radial pressure is too small, the longitudinal force is relatively small and the clamp mechanical connection is easy to fall off.

When using the core concrete connection method, concrete mixed with an expansion agent is poured inside the PHC pipe pile and longitudinal reinforcement is installed (as shown in Figure 1(b)). The longitudinal reinforcement is then connected to the reaction beam, and the uplift load taken by the anchor pile is transmitted through the bonding force between the core concrete and the inner wall of the PHC pipe pile. The length of the core concrete depends on the bond strength between the core concrete and the inner wall of the PHC pipe pile and is generally between 0.3 and 0.6 MPa [12]. The strength of the core concrete should not be less than C30, and the length should not be less than twice the diameter of the pile. Compared with the clamping connection method, the reaction force provided by the anchor pile using the core concrete connection method is easier to control. However, when pouring the core concrete, it is difficult to control the quality of concrete vibration and wet operation, and there is a high labor cost and long maintenance period, which affects the PHC pile bearing capacity test. If the longitudinal reinforcement is damaged during the PHC pile bearing capacity test, it will also affect the connection between the PHC pile and the foundation.

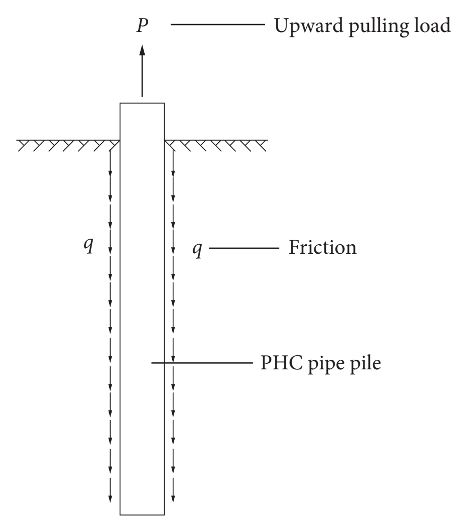

FIGURE 2: Mechanical behavior of the pile when using the clamping or core concrete connection method.

When using either the clamping or the core concrete connection method for PHC pipe piles (as shown in Figure 2), the PHC pipe pile carries a tensile force under the upward pulling load, which is similar to the uplift pile in engineering practice [9, 10]. As the upward pulling load increases, the prestress of the PHC pipe pile begins to unload, and the larger the upward pulling load is, the greater the unloading value of the prestress is, which will cause the pile to experience tensile stress or even fracture. If cracks appear in the PHC pipe pile, the integrity category of the pile is considered to be class IV, which means that the pile has serious defects and does not meet the requirements of GB 50202-2018 [14]. Therefore, when PHC pipe piles are used as anchor piles, the magnitude of the reaction force provided by the anchor pile needs to be checked not only against the side friction resistance of the PHC pipe pile but also against the pile cracks. When it is necessary to check the cracks in the pile, the reaction force provided by the PHC anchor pile may be less than the requirement of the reaction device for the single pile bearing capacity test. At the same time, the upward pulling load causes prestress loss in the PHC pipe pile, which has an adverse effect on the durability and safety of the PHC pipe pile. It should be noted that Wei et al. [9], Hao et al. [10], and Xi et al. [11] analyzed the geometrical and mechanical characteristics of PHC pipe piles through experimental tests and numerical simulations. Investigations included the compressive and pull-out performance of PHC pipe piles, as well as the reaction force device used in load tests. Results highlighted the necessity of developing a new type of reaction force device for determining the load-bearing capacity of PHC pipe piles and the issues that should be considered in the analysis. The findings provided a research direction for the proposed novel reaction force device in this paper.

Grout is widely utilized in sleeve connection of prefabricated structures due to its low cost and convenient construction [15–17]. To overcome the shortcomings of the clamping and core concrete connection methods, a core grout connection method is proposed by the authors based on the stress analysis and geometric characteristics of PHC pipe piles. To apply the core grout connection method to the load-bearing capacity testing of PHC pipe piles, experimental research is also conducted on the bonding performance between the core grout and the inner wall of the PHC pipe pile. The influence of factors such as the inner diameter of the PHC pipe pile, the strength of the core grout, the grouting length, and the curing time on the bonding performance between the core grout and the inner wall of the PHC pipe pile is analyzed, and a calculation formula for the bonding bearing capacity between the core grout and the inner wall of the PHC pipe pile is developed. The main contribution of this paper is to propose a new type of reaction device for determining the bearing capacity of PHC piles, conduct experimental research on the bond performance between the grout and the inner wall of the PHC piles and establish a calculation formula to determine the bond bearing capacity.

1.1. The Proposed Core Grout Connection Method. In the proposed core grout connection method (Figure 3), core grout is poured to the bottom of the PHC pipe pile, and deformed reinforcing bars are used as connecting components with the upper reaction beam. The grout has the characteristics of fast early strength development, high later strength, and vibration-free, which is to pour inside the PHC pipe pile [18, 19]. The deformed reinforcing bars have high-strength and high elastic modulus, and are equipped with connectors, which is convenient for connection [20, 21]. For the grout, the fast early strength development can accelerate the installation progress of the reaction device while the high later strength can provide a higher bond strength. The vibration-free characteristic of the grout can ensure that the core grout is fully bonded to the inner wall of the PHC pipe pile. For the deformed reinforcing bars, the high strength can reduce the amount of steel bars used while the high elastic modulus can reduce the deformation of the reaction device. The connector can achieve rapid steel bar connection, rapid disassembly, and recycling of steel bars. After the single pile bearing capacity test is completed, the deformed reinforcing bars can be removed at the connector without affecting the connection between the PHC pipe pile and the bearing platform.

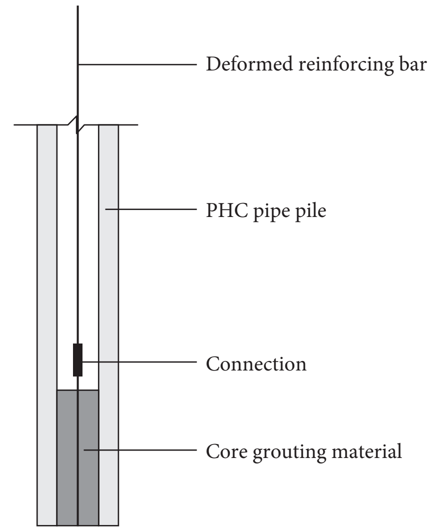

Figure 3: The core grout connection method.

At the technical level, the core grout connection method has the advantages of convenient construction, strong controllability of the connection quality and low cost compared with the clamping and core concrete connection methods. At the theoretical level, the upward pulling load carried by the PHC pipe pile using the core grout connection method is transmitted to the PHC pipe pile through the bonding force between the core grout and the inner wall of the PHC pipe pile. As the upward pulling load acts deep in the PHC pipe pile, the frictional resistance along the pile sides mainly distributes on the upper part of the core grouting material. Thus, the upward pulling load and the frictional resistance constitute a pair of balancing forces. Under these two forces, the PHC pipe pile will not experience prestress unloading or pile tensile stress, as shown in Figure 4.

2. Experimental Tests

2.1. Design and Preparation of Specimens. The experiment tests are mainly used to examine the influence of four factors, namely, the inner diameter of the PHC pipe pile, the strength, the grouting length, and the curing time of the core grout, on the bonding performance between the core grout and the inner wall of the PHC pipe pile. The design parameters of the specimens are listed in Table 1 according to the partial factor design method [22].

The main part of the test specimen is a pile section, which is cut from a complete PHC pile using a clamping cutting

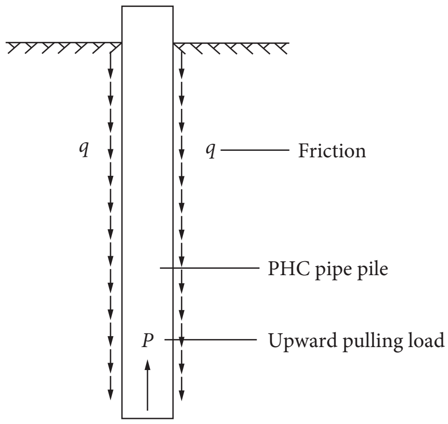

Figure 4: Mechanical behavior of the pile when using the core grout connection method.

machine. To simulate the in situ conditions of using the PHC pipe piles as anchor piles, the inner wall of the PHC pipe pile is not treated with surface chipping, and only tap water is applied to fully wet the inner wall of the PHC pipe pile. Coarse sand is laid at the bottom of the pile section to achieve the grouting length L of the core grout in the PHC pipe pile by changing the thickness of the coarse sand. To reduce the end effect caused by the tensile and upward pulling load during the loading process, the top of the core grout is 1.5 times the pile diameter away from the top of the PHC pipe pile. To ensure that there is no relative sliding between the deformed reinforcing bar and the core grout during the loading process, the lower end of the deformed reinforcing bar is mechanically anchored, as shown in Figure 4. Before filling the core grout, keep the PHC pipe pile vertical, position the deformed reinforcing bar to the center of the PHC pipe pile section, and pour the core grout from top to bottom into the PHC pipe pile until the design elevation is reached. The test specimen is then cured under natural conditions for the designed curing time.

The curing time for specimens numbered 1–10 is 3 days. The purpose of using the strength index with a curing age of 3 days is to achieve rapid installation of the anchor pile reaction device using the core grout connection method.

2.2. Testing Materials and Material Performance. The core grout was purchased from Zhongdi Xinya Building Materials Co., Ltd., and its main components include high-strength ultra-fine cement, fine aggregate, expansion agent, slag, and so forth. The strength of the hardened core grout is controlled by the water-to-material ratio, the water-to-material ratios for specimens B-C40 and B-C80 are 0.135 and 0.110, respectively, while those for the remaining specimens are 0.125. According to GB/T17671-2021 [23], specimens with sizes of $40 \times 40 \times 160$ mm are prepared, and the tensile strengths f_t of the core grout at 3 days are determined as shown in Table 1.

According to GB/T 228.1-2021 [24], uniaxial tensile tests are performed on deformed reinforcing bars with diameters of 25 mm. The average yield strength is found to be 1,120 N/mm^2. The PHC pipe pile is taken from a project in Zhengzhou Airport Economy Comprehensive Experimental Zone, with an effective prestress of 6.0 N/mm^2, an outer diameter of 400 mm, inner diameters of 200 and 220 mm, respectively, a pile strength grade of C70. There are 12 prestressed reinforcement bars with a diameter of 12.6 mm.

2.3. Specimen Loading and Measurement Set-Up. In this paper, the vertical pulling load is applied to the gout, and a displacement lever is designed for measurement of displacement of grout, which is different from existing methods [15, 16]. As shown in Figure 5, a hydraulic jack is used to apply tensile and pulling loads to the specimen. The hydraulic jack is placed on the top of the PHC pipe pile, and the deformed reinforcing bar passes through the hydraulic jack. A steel plate and a load transducer are installed at the top of the hydraulic jack, and a nut is installed at the upper end of the deformed reinforcing bar. The deformed reinforcing bar, the hydraulic jack, and the PHC pipe pile form a self-balancing force system. The load applied by the hydraulic jack is transmitted through the steel plate to the deformed reinforcing bar, which then transfers the tensile and pulling loads to the core grout through the bonding interface. The bond is generated between the core grout and the inner wall of the PHC pipe pile. The reaction force at the base of the hydraulic jack is transmitted to the PHC pipe pile through the steel plate, forming a balanced force system between the hydraulic jack and the PHC pipe pile.

According to the self-balancing transmission system of the loading system, the force transmission diagram of the core grout and the PHC pipe pile is drawn according to the section method, as shown in Figure 6. Due to the mechanical anchorage of the deformed reinforcing bar at the lower end, it is assumed that there is no relative slippage between the deformed reinforcing bar and the core grout when measuring and analyzing the relative slippage between the core grout and the inner wall of the PHC pipe pile. The weight of the core grout is much smaller than the vertical tensile load, so the influence of the weight of the core grout on the measurement of the tensile load can be ignored. The range of the hydraulic jack is 1,000 kN, and a monotonic loading system is used to apply tensile load to the specimen at a speed of 50–100 N/S until the core grout is pulled out. The tensile load is measured through the load transducer, and when the core grout is in a semihardened state, the displacement lever shown in Figure 5 is vertically inserted into the core grout, and the displacement sensor is set up on the displacement guidance rod. By measuring the upward displacement of the displacement guidance rod, the sliding displacement between the core grout and the inner wall of the PHC pipe pile can be obtained. The DH3816 static strain tester is used to measure the tensile load and the sliding displacement.

3. Testing Results

3.1. Failure Patterns of Specimens. Figure 7 shows the failure modes of the tested specimens. Under the vertical pulling load, the deformed reinforcing bars and the core grout move upward synchronously. When the core grout is about

Table 1: Specimen design and material properties.

Index	Specimen no.	D (mm)	f_t (N/mm^2)	L (mm)	Curing time (days)	τ_u (N/mm^2)	φ
1	A-R200	200	3.98	200	3	2.10	0.53
2	A-R220	220	3.98	200	3	2.00	0.50
3	B-C40	200	3.35	200	3	1.94	0.58
4	B-C80	200	4.92	200	3	2.35	0.48
5	C-L100	200	3.98	100	3	2.15	0.54
6	C-L300	200	3.98	300	3	2.04	0.51
7	C-L400	200	3.98	400	3	2.01	0.51
8	C-L500	200	3.98	500	3	2.01	0.51
9	C-L600	200	3.98	600	3	2.03	0.51
10	D-A7	200	3.98	200	7	2.18	–
11	D-A14	200	3.98	200	14	2.23	–
12	D-A28	200	3.98	200	28	2.59	–

Note. D is the inner diameter of the PHC pipe pile, f_t is the tensile strength of core grout at a curing time of 3 days, L is the grouting length of the core grout in the PHC pipe pile, τ_u is the bond strength, and φ is the interface bonding coefficient.

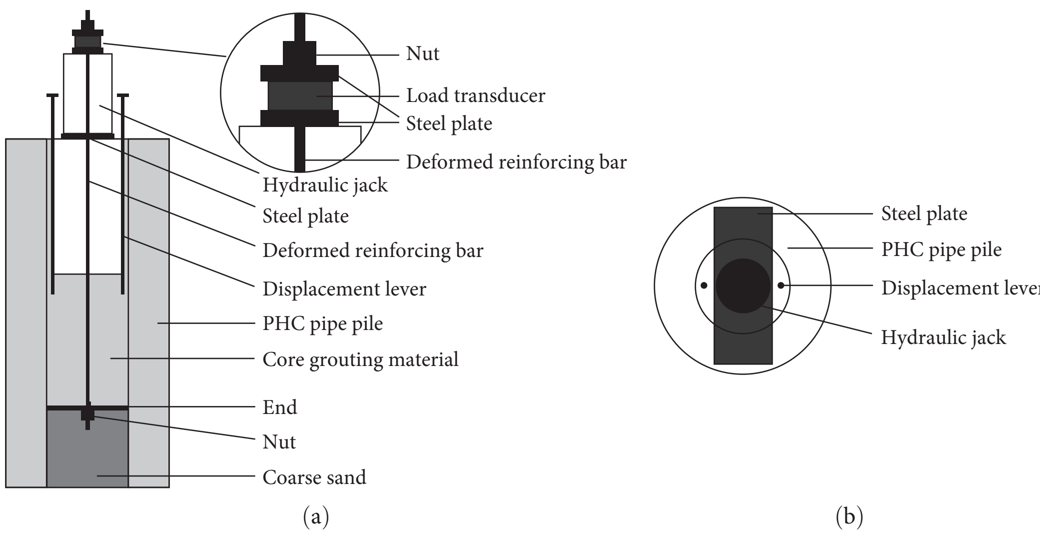

Figure 5: Loading device. (a) Elevation view and (b) top view.

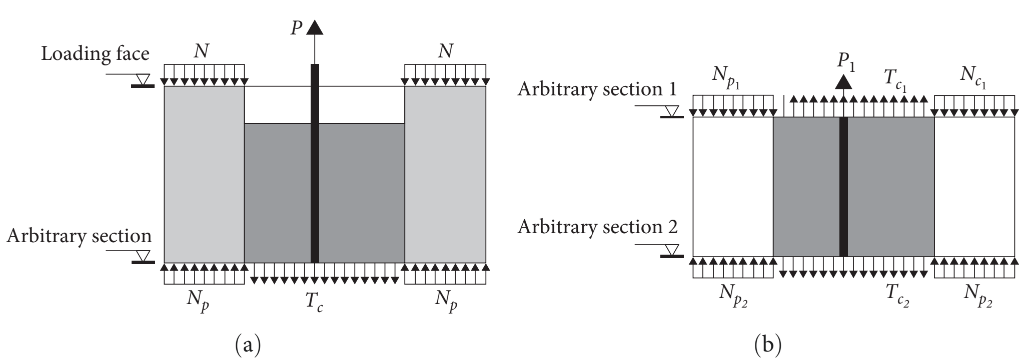

Figure 6: Schematic diagrams of loaded specimens. (a) Loading face to an arbitrary section and (b) an arbitrary section to another arbitrary section.

to peel off from the inner wall of the PHC pipe pile, a slight cracking sound occurs. When the vertical pulling load reaches its maximum value, the core grout is completely pulled out, as shown in Figure 7(a). The slurry on the inner wall of the PHC pipe pile shows a wavy pattern, causing uneven circumferential bonding stress. This ultimately leads to circumferential cracks in the core grout with the deformed reinforcing bar as the center in some specimens, as shown in

(a) (b)

Figure 7: Failure modes of the specimens. (a) Pull out and (b) circumferential crack.

Figure 7(b). After the test is completed, there is no relative displacement between the deformed reinforcing bars and the core grout, no cracks appear on the outer surface of the PHC pipe pile and there is no peeling between the slurry on the inner wall of the PHC pipe pile and the concrete aggregate on the inner wall. This indicates that the relative relationship between the deformed reinforcing bars and the core grout is consistent with the assumption. Under the self-balancing force system, the PHC pipe pile mainly bears vertical pressure, and the vertical compressive stress does not exceed its compressive strength. The bond strength between the slurry on the inner wall of the PHC pipe pile and the inner wall of the PHC pipe pile is greater than the bond strength between the core grout and the inner wall of the PHC pipe pile.

3.2. Analysis of Experimental Results. The main indicator for evaluating the bonding performance between the grout and the inner wall of PHC piles is the average bond stress.

$$\tau = \frac{P}{\pi d L}, \tag{1}$$

where P represents the axial pull-out load, d represents the inner diameter of the PHC pipe pile, and L represents the grouting length of the core grout. The average bond stress obtained when the maximum value P_u is reached is called the bond strength. Pull-out tests are performed on 12 specimens, and the bond stress–slip curves are obtained, as shown in Figure 8. It can be drawn that all the average bond strength test results are higher than that between the core concrete and the inner wall of the PHC pile. The bonding strength of the former is greater than 2 MPa, while the latter is between 0.3 and 0.6 MPa [12].

3.2.1. Effect of the Inner Diameter of the PHC Pipe Pile. PHC piles are taken from practical engineering projects, with inner diameters of 200 and 220 mm, respectively. The PHC piles are produced using a centrifugal method, with a layer of cement slurry attached to the inner wall. The cement slurry on the inner wall of the PHC piles has a thickness of 50–150 mm and appears in a wave-like shape. The wave heights of specimens A-R200 and A-R220 are roughly the same. Note that the larger the inner diameters of the specimens are, the larger their internal surface areas are, and the more dispersed the distribution of the cement mortar wave shape is. Thus, this results in a smaller roughness of the internal surface. The roughness of the inner surfaces of PHC piles is one of the main factors affecting the bond strength between the core grout and the inner wall of the PHC pile. Specimen A-R200 has a smaller inner diameter than the specimen A-R220. Therefore, specimen A-R200 has greater inner surface roughness and thus higher bond strength. However, the difference is small with only a maximum value of 5%, as shown in Table 1. The roughness of the inner surface of PHC piles not only affects the bond strength between the core grout and the inner wall of the PHC pile, but also affects the bond stress under the same slip conditions. This is mainly reflected in the fact that the τ–s curve slope of specimen A-R200 is slightly higher than that of specimen A-R220, as shown in Figure 8(a).

3.2.2. Effect of the Strength of Core Grout. Figure 8(b) and Table 1 present the bond strength–slip curves and bond strength of specimens B-C40, A-R200, and B-C80. There is a positive correlation between the tensile strength and the strength grade of the core grout. The bond strength between the core grout and the internal wall of the PHC pipe pile depends on the tensile strength of the core grout. From the experimental results, it can be concluded that the higher the strength grade of the core grout is, the greater the bond strength between the core grout and the internal wall of the PHC pipe pile is, and the steeper the slope of the bond stress–slip curve is.

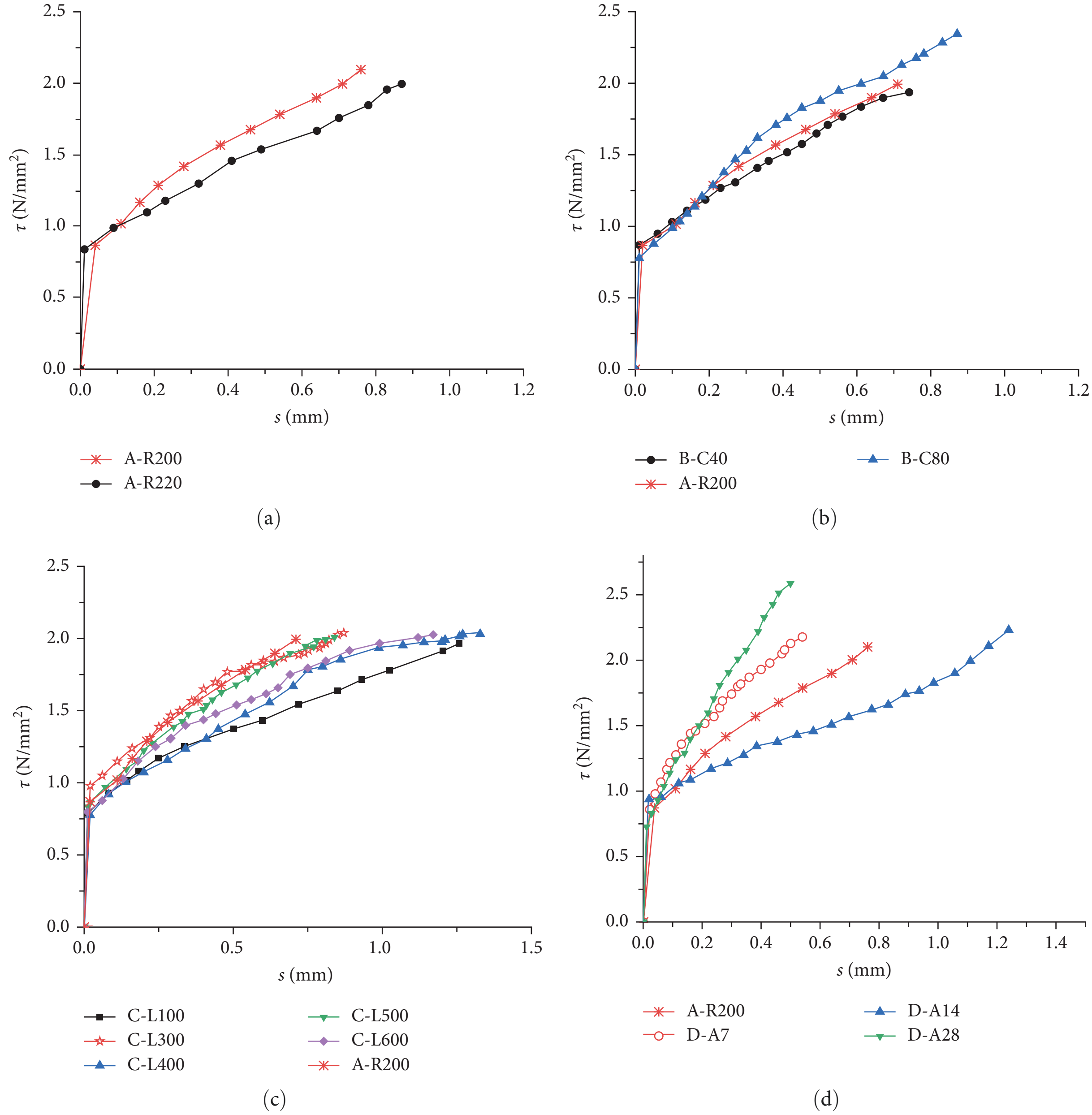

FIGURE 8: Bond stress–slip curves. (a) Effect of the inner diameter of the PHC pipe pile, (b) effect of the strength of core grout, (c) effect of the grouting length, and (d) effect of the curing time of the core grout.

3.2.3. Effect of the Grouting Length. The bond stress–slip curves and the bond strengths of specimens C-L100, A-R200, C-L300, C-L400, C-L500, and C-L600 are presented in Figure 8(c) and Table 1. From the test results, it can be observed that the bond stress–slip curves exhibit slight differences due to the varying grouting lengths of the specimens, but the differences are not significant. The bond strength decreases with the increase of the grouting length, and tends to stabilize, with a maximum difference of no more than 10% between the maximum and minimum bond strength values. The roughness of the wavy slurry on the inner wall of the PHC pile shows a certain degree of randomness while its distribution along the length of the PHC pile has a certain degree of uniformity. Within a unit length range, the undulation of the wavy slurry is relatively small, and its effect on the mechanical interlocking force between the core grout and the inner wall of the PHC pile is minimal.

3.2.4. Effect of the Curing Time of the Core Grout. The bond stress–slip curves and bond strengths of specimens C-L100, A-R200, C-L300, C-L400, C-L500, and C-L600 are shown in Figure 8(d) and Table 1. Based on the experimental results, the bond strength between the core grout and the inner wall of the PHC pipe pile increases with the increase of the curing time and the increment of the bond strength is up to 20%. The bond strength between the core grout and the inner wall of the PHC pipe pile for a curing time of 3 days reaches about 80% of the corresponding value when the curing

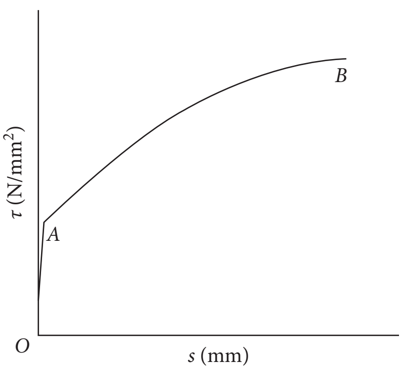

FIGURE 9: Schematic diagram of bond stress–slip curves.

time is 28 days. Note that the bond strength depends on the tensile strength of the core grout, which increases with the curing time. Based on the information provided by the manufacturer, the compressive and tensile strengths of the core grout at the curing time of 3 days can reach 80%–90% of those at the curing time of 28 days. Experimental results show that the time required to complete site leveling and equipment installation for the PHC pipe pile bearing capacity test is about 3 days. Thus, the bond strength between the core grout and the inner wall of the PHC pipe pile can meet the requirements of the core grout connection method. The load-bearing capacity test is conducted one by one for the PHC pipe piles, and the duration of each test is 1–2 days. If the reaction force provided by the reaction device of the first tested pile meets the requirements, the reaction force provided by the reaction devices of all subsequent tested piles can also meet the requirements.

4. Calculation of the Loading Capacity

The bonding performance of the interface between the core grout and the inner wall of the PHC pipe pile belongs to the problem of interface bonding between new and old materials at different solidification times. This is similar to the bond mechanism between steel bars and concrete. The bond mechanism between steel bars and concrete has been studied by many researchers with a focus on bond stress–slip curves [25, 26]. As shown in Figure 8, the patterns of the bond stress–slip curves are roughly similar and can be expressed by the same characteristic curve. The bond stress–slip curve can be divided into two stages, as shown in Figure 9.

(1) From O to A in Figure 9. At the initial loading stage, there is no relative slip between the core grout and the inner wall of the PHC pipe pile. Shear stress is generated on the inner wall of the PHC pipe pile, which is mainly carried by the chemical bonding force at the interface between the core grout and the inner wall of the PHC pipe pile. As the axial tensile load further increases, the bond stress near the loaded end of the PHC pipe pile gradually increases. When the bond stress exceeds the chemical bonding force at the interface between the core grout and the inner wall of the PHC pipe pile, slight slip occurs at the loaded end. Gradually, the slight slip extends toward the far end of the loaded end within the grouting length range, resulting in relative slip. The corresponding load is called the sliding load, and the average bond stress is approximately 0.6 N/mm^2. The core grout does not contain coarse aggregates and has good flowability, which can fully fill the inner wall of the PHC pipe pile. Thus, the core grout and the inner wall of the PHC pipe pile have a strong chemical bonding force.

(2) From A to B in Figure 9. As the load increases, the relative slip between the core grout and the inner wall of the PHC pile further increases, which is different from that between steel bar and concrete [27, 28]. The bond stress increases with the increase of slip displacement, and the slope of the bond stress–slip curve gradually decreases, but the magnitude of the slope change is not significant. In this stage, the chemical bond strength gradually decreases until it disappears, and the mechanical interlocking force and the friction force between the core grout and the inner wall of the PHC pile play a major role. The core grout contains an expansive agent. The radial compression of the core grout by the inner wall of the PHC pile increases the friction force between them. When the bond stress–slip curve reaches the peak value and the bond stress between the core grout and the inner wall of the PHC pile reaches the bond strength, the core grout is pulled out and the specimen fails rapidly.

Under the axial tensile load, the distribution of the bond stress between the filled core grout and the inner wall of PHC piles is considered as a one-dimensional problem. It is assumed that the bond stress at the contact surface varies with the tensile strength and z, that is, $\tau = \tau(f_t, z)$ [16]. To facilitate engineering applications, the average bond strength τ_u is used instead of $\int_0^L \tau(f_t, z)dz$, and it is assumed that τ_u is only related to the tensile strength f_t of the filled core grout, that is:

$$\tau_u = \varphi f_t, \tag{2}$$

where φ is the interface bond coefficient.

Based on Table 1, when the curing time for the C60 concrete strength grade is 3 days, the average bond strength τ_u between the grout and the inner wall of the PHC pipe pile has a minimum value of 2.0 N/mm^2 and an average of 2.05 N/mm^2. The minimum value of the interface bond coefficient at 3 days is 0.48. The average of the interface bond coefficient at 3 days is 0.52 and is taken to be 0.49 for a reliability of 95%. Both the bond strength and bond coefficient between the grout and the PHC pipe pile wall are higher than the corresponding values of the core concrete and the PHC pipe pile wall [16].

JGJ106-2014 [5] stipulates that to determine the bearing capacity of PHC pipe piles, the maximum added load should not be less than twice the characteristic value of the vertical compressive bearing capacity of a single pile required by design. In this experiment, the bonding bearing capacity is calculated with a safety factor of 2.0. The design calculation formula for the bearing capacity N_t is expressed as follows:

$$N_t = \frac{\pi \varphi d L f_t}{K}, \quad (3)$$

where K is the safety factor.

5. Conclusions

A core grout anchor device has been proposed based on the geometric characteristics and mechanical performance of PHC pipe piles used as anchor piles. This device has the advantages of convenient construction, strong controllability of connection quality, and low cost. Moreover, the pile will not experience prestress unloading or tensile stress under upward pulling load. Experimental tests have also been conducted to investigate the bonding performance between the core grout and the inner wall of the PHC pipe pile. The following conclusions are drawn based on the experimental results:

(1) The bond strength between the core grout and the inner wall of PHC pipe piles decreases with the increase of the inner diameter of the pipe piles, but the difference is small within 5%. It also decreases with the increase of grouting length and gradually tend to be stable. The maximum and the minimum bond strength values have a maximum different of 10%. The higher the strength grade of the core grout is, the greater the bond strength between the grout and the inner wall of the PHC pipe pile is. The bond strength between the core grout and the inner wall of the PHC pipe pile increases with the increase of curing time within 28 days of curing time. The bond strength at 3 days can meet the requirements of the PHC pile bearing capacity test.

(2) The bond stress–slip curve between the core grout and the inner wall of PHC pipe piles can be divided into two stages. In the first stage, the chemical bonding force between the core grout and the PHC pipe pile is mainly responsible for longitudinal tensile and pull-out loads, and the bond stress–slip curve is linear. In the second stage, the mechanical interlocking force and the frictional force between the core grout and the PHC pipe pile are mainly responsible for longitudinal tensile and pull-out loads, and the slope of the bond stress–slip curve decreases with the increase of slip, and when the bond strength is reached, the core grout is pulled out, and the specimen fails quickly.

(3) Under axial tensile and pull-out loads, the distribution of the bond stress between the core grout and the inner wall of PHC pipe piles is considered as a one-dimensional problem, and the calculation formula for the bonding bearing capacity between the core grout and the inner wall of PHC pipe piles is established to calculate the reactive force provided by the core grout anchor device.

Data Availability

The experimental 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.

References

[1] X. Huang, Y. Mei, Y. Wangren, T. Li, B. Lei, and W. Zhao, “An analysis on comparison of the static load test performed to post-grouted pile foundation with Chinese, American and European standard,” *Tehnički Vjesnik*, vol. 27, no. 3, pp. 978–985, 2020.

[2] “Abu Dhabi international building codes,” Department of Municipal Affairs, 2013.

[3] ASTM, *Standard Test Methods for Deep Foundations under Static Axial Compressive Load*, ASTM International, 2013.

[4] N. P. Zade, S. T. John, P. Sarkar, and R. Davis, “Safety assessment of kentledge construction for pile foundation,” *Practice Periodical on Structural Design and Construction*, vol. 27, no. 2, Article ID 05022001, 2022.

[5] JGJ106-2014, *Technical Code for Testing of Building Foundation Piles*, China Building Industry Press, 2014.

[6] Civil Engineering and Building Structures Standards Committee, *BS8004-1986 British Standard Code of Practice for Foundations*, Board of BSI, England, 1986.

[7] Z. Yang, Y. Lei, and G. Li, “Experimental and finite element analysis of shear behavior of prestressed high-strength concrete piles,” *International Journal of Civil Engineering*, vol. 21, pp. 219–233, 2023.

[8] T. Wang, Z. Yang, H. Zhao, and W. Wang, “Seismic performance of prestressed high strength concrete pile to pile cap connections,” *Advances in Structural Engineering*, vol. 17, no. 9, pp. 1329–1342, 2014.

[9] Y. Wei, D. Wang, J. Li et al., “Evaluation of ultimate bearing capacity of pre-stressed high-strength concrete pipe pile embedded in saturated sandy soil based on in-situ test,” *Applied Sciences*, vol. 10, no. 18, Article ID 6269, 2020.

[10] F. Hao, J. L. Liu, Y. Y. Li, and J. G. Cai, “Numerical simulation on uplift performance of hooped joint of PHC pipe pile,” *Industrial Architecture*, vol. 52, no. 6, pp. 25–30, 2022.

[11] Y. J. Xi, P. Huang, and Y. T. Ren, “Application research on using pipe pile as anchor pile in static load test,” *Journal of Water Resources and Architectural Engineering*, vol. 10, no. 6, pp. 53–55, 2012.

[12] F. Li, Z. S. Guo, Z. J. An, and J. L. Liu, “Study on axial pull-out performance test of PHC pipe pile filled with core concrete,” *Industrial Architecture*, vol. 52, no. 6, pp. 7–16, 2022.

[13] Q. Fang, Z. Yang, C. Zhang, L. Yi, and X. Fu, “Influence of test method and Poisson’s ratio effect on pullout performance of anchor bolt in pile,” *KSCE Journal of Civil Engineering*, vol. 24, pp. 3775–3784, 2020.

[14] GB 50202-2018, *Standard for Acceptance of Construction Quality of Building Foundation*, China Planning Press, Author:

Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2018.

[15] J. Chen, C. Zhao, F. Ding, and P. Xiang, "Experimental study on the seismic behavior of precast concrete column with grouted corrugated sleeves and debonded longitudinal reinforcements," *Advances in Structural Engineering*, vol. 22, no. 15, pp. 3277–3289, 2019.

[16] J. Chen, C. Zhao, F.-X. Ding et al., "Mechanical performance of the grouted lapped double reinforcements anchored in embedded corrugated sleeves," *Structures*, vol. 28, no. 3, pp. 1354–1365, 2020.

[17] J. Chen, X. Chen, F.-X. Ding et al., "Mechanical performance of overlap connections with grout-filled anchor reinforcements in embedded metal corrugated pipe," *Archives of Civil and Mechanical Engineering*, vol. 20, no. 4, Article ID 128, 2020.

[18] A. Senkaya, E. B. Toka, and M. Olgun, "Effects of cement grout characteristics on formation and strength of jet grouting columns," *Arabian Journal for Science and Engineering*, vol. 47, pp. 13035–13047, 2022.

[19] Y. Sun, P. Zhang, W. Yan, J. Wu, and F. Yan, "Grouting material development and dynamic grouting test of broken rock mass," *Journal of Materials in Civil Engineering*, vol. 34, no. 5, Article ID 04022072, 2022.

[20] A. I. Zaky, A. El-Morsy, and T. El-Bitar, "Effect of different cooling rates on thermomechanically processed high-strength rebar steel," *Journal of Materials Processing Technology*, vol. 209, no. 3, pp. 1565–1569, 2009.

[21] H.-B. Pan, M.-J. Zhang, W.-M. Liu et al., "Effects of micro-alloying and production process on precipitation behaviors and mechanical properties of HRB600," *Journal of Iron and Steel Research International*, vol. 24, pp. 536–543, 2017.

[22] D. Montgomery, *Design and Analysis of Experiments*, John Wiley & Sons Inc, New York, 6th edition, 2005.

[23] GB/T17671-2021, *Test Method of Cement Mortar Strength (ISO Method)*, Standards Press of China, 2021, 2021.

[24] GB/T 228.1-2021, "Metallic materials-tensile testing at ambient temperature," Physical Testing and Chemical Analysis Part A Physical Testing, 2021.

[25] M. Harajli, B. Hamad, and K. Karam, "Bond-slip response of reinforcing bars embedded in plain and fiber concrete," *Journal of Materials in Civil Engineering*, vol. 14, no. 6, pp. 503–511, 2002.

[26] J. Murcia-Delso and P. B. Shing, "Bond-slip model for detailed finite-element analysis of reinforced concrete structures," *Journal of Structural Engineering*, vol. 141, no. 4, Article ID 04014125, 2015.

[27] A. Casanova, L. Jason, and L. Davenne, "Bond slip model for the simulation of reinforced concrete structures," *Engineering Structures*, vol. 39, pp. 66–78, 2012.

[28] G. Xu, J. Xiang, Q. Wang, X. Xiang, and Y.-L. Zhang, "Calculation of relative slip between steel bars and concrete," *Construction and Building Materials*, vol. 202, pp. 537–545, 2019.