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Settlement Analysis of Pre-stressed Concrete Pipe-Pile Foundations in Soft Ground: A Case Study

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Abstract: This study presents a detailed examination of the implementation of prestressed concrete pipe-piles in the soft ground of a coastal region in Guangdong province, China. The discussion is initiated by an exploration of the prestressed concrete pipe-pile and the unique challenges brought forth by the soft ground conditions, characterized by low strength, high compressibility, and plasticity. Subsequently, the paper delves into the practical application of prestressed pipe-piles in the soft ground, shedding light on potential limitations and pertinent issues. The intent of this analysis is to furnish a comprehensive guide for foundation design and construction in soft ground conditions, thereby equipping decision-makers and practitioners with valuable insights to navigate analogous situations effectively.

1. Introduction

With the acceleration of urbanization, more and more construction projects need to be carried out under complex geological conditions. The coastal area of the Pearl River Estuary in Guangdong Province has an important and unique geographical location. The foundation of this area is mainly composed of river alluvial layers and marine sedimentary layers, among which silt and silty soil are the main geological features. Also, due to the influence of marine dynamics such as tides and waves in the Pearl River estuary, the foundation soil may also have a high risk of earthquake liquefaction. Therefore, these characteristics need to be fully considered in the design and construction process, and corresponding foundation treatment measures should be taken to ensure the stability and safety of the project. Prestressed pipe-pile, as a common form of pile possesses high bending bearing capacity, small deformation, and good settlement control ability, and are widely used in foundation engineering in soft ground.

Research on the application of prestressed pipe-piles in soft ground has been explored by some scholars. Cairo et al. used the boundary element method based on the stiffness matrix method to study the key characteristics of soil-structure interaction (SSI) and effectively evaluated the effects of soil-structure interaction with pile foundations under steady-state conditions[1]. HE et al. explored the working mechanism and bearing characteristics of bottom-lift piles through the experimental data of pile-bearing capacity tests of a certain project and numerical simulation methods, and they proposed corresponding design suggestions[2]. LIU Jinbo et al. concluded that the settlement deformation of prefabricated extruded piles increases with the decrease of pile spacing through the comparative analysis of the influence of pile spacing on settlement deformation[3]. CHEN Fan et al. analyzed several instances of prestressed pipe-pile projects in soft ground and found that pile position skewness is mostly caused by improper handling during pit excavation, and pile position skewness often leads to cracking and even breaking of pile foundations[4]. WANG Bei et al., in conjunction with the problems in the construction of static pressure prestressed pipe-piles in a certain project's soft ground, deeply explored the selection of pile foundation construction schemes and the causes and treatment methods of the problem of pipe-piles under-delivery[5]. YU Jianfei et al. studied the influence of pile-soil relative displacement and pile-soil relative displacement rate on the pull-down load of test piles, negative friction coefficient, and neutral point through pull-down load tests on newly installed prestressed pipe-piles after site overload preloading unloading[6]. LI Songyan et al., combined with the example of pile foundation engineering in the first opening area of a certain project, explained a series of quality problems that will arise when pile foundation construction is carried out in ultra-deep silty soil and gave treatment methods for unqualified piles with technical means such as layered excavation, correction, and core filling so that the quality of piles meets the national specification requirements[7]. However, there is relatively little research on the engineering practice of prestressed pipe-piles in soft ground, especially on the issue of foundation settlement.

This paper takes the foundation settlement problem of a one-story frame structure in a coastal area of Guangdong Province as an example and conducts in-depth research on the application case of prestressed pipe-piles in soft ground. By introducing the project overview, geological conditions, and field testing conditions in detail, the causes of foundation settlement are deeply analyzed. Meanwhile, the practical application experience of prestressed pipe-piles in soft ground, as well as possible problems and limitations, are summarized. The research results will provide reference and guidance for the design and construction of foundation engineering in soft ground, and promote the development and progress of related fields; in addition, the research results can also provide a valuable reference for decision-makers and practitioners who encounter similar problems in engineering practice.

2. Characteristics of Soft Ground

Soft soil is mainly composed of clay, sandy clay, silty clay, and organic matter, with small particles and loose structures. The water content of this soil is usually very high, reaching 60% to 80%, or even higher. Due to its small particles and high water content, the permeability of soft soil is poor, making it difficult to drain[8].

The engineering characteristics of soft soil are mainly low strength, high compressibility, and plasticity. These characteristics make it easy for soft soil to produce a large amount of deformation and settlement when subjected to load. In addition, the shear strength of soft soil is low, and it is easy to slide and shear failure. These characteristics pose great challenges to the construction of engineering in soft soil sites. Nikolaos Makrakis et al. conducted a series of numerical analyses on a typical pipeline buried in sandy soil layers with different thicknesses and mechanical properties in a study on onshore high-pressure natural gas pipelines, studying the impact of soft soil layers on seismic dynamic damage[9].

The main challenges faced by the construction of soft soil sites include difficult foundation treatment, large foundation settlements, high groundwater levels, and complex geological conditions. These challenges need to be fully considered and dealt with in engineering design and construction to ensure the safety and stability of the project. Georgios Nikitas et al. proposed a low-cost liquefaction prevention technology in a study on sand-tire debris mixed foundations[10]. This technology uses the rubber of waste tires as the foundation material for small low-rise residential buildings, which can effectively prevent soil liquefaction and is also an effective seismic isolation system that can be optimally adjusted.

3. Characteristics of Prestressed Pipe-pile

Prestressed pipe-pile foundation is a common form of pile foundation, which improves the bearing capacity and rigidity of pipe-pile by applying pre-stress inside it. The main features of prestressed pipe-pile are high bearing capacity, good rigidity and toughness, and excellent bending resistance. In addition, the fast construction speed and small environmental impact of prestressed pipe-pile are also important advantages[11]. Another important characteristic of prestressed pipe-pile is that their performance under lateral cyclic loading is significantly better than ordinary pipe-pile, with significant improvements in bending performance and energy dissipation capacity[12].

The construction methods of prestressed pipe-pile mainly include the manufacture, transportation, installation, and application of pre-stress of pipe-pile. The manufacture of pipe-pile is usually carried out in factories to ensure quality and dimensional accuracy. The installation of pipe-pile usually uses a pile driver to drive the pipe-pile into the foundation by vibration or impact. The application of pre-stress is usually carried out after the installation of the pipe-pile, by stretching steel bars or steel cables inside the pipe-pile and then anchoring them at the top and bottom of the pipe-pile to apply pre-stress[11].

However, prestressed pipe-pile also has its limitations. First, the manufacture and installation of prestressed pipe-pile require special equipment and technology, which may increase the cost of the project. Secondly, the design and construction of prestressed pipe-pile need to consider many factors, such as geological conditions, the size of the pipe-pile, and the size of the pre-stress, which requires engineers with rich experience to design and construct. Finally, the long-term performance of prestressed pipe-pile, such as durability and corrosion resistance, needs further research[13].

4. Application of Prestressed Pipe-piles in Soft Ground

4.1 Project Overview

The project is located in a coastal area of Guangdong Province. The structure is a reinforced concrete frame structure, single-layer, with a layer height of 6 m and a total construction area of about 650m^2. The project started at the beginning of 2021, and in October of the same year, it was found that the structural foundation had a severely uneven settlement, causing the upper structure to tilt and a large number of structural and non-structural components to crack, seriously affecting the serviceability of the house.

4.1.1 Geological Conditions

The geological conditions within the project site are shown in Table 1, and the recommended values of pile foundation design parameters are shown in Table 2. The soil layers from top to bottom within the site are: fill soil, silt, silty soil, gravelly clay, completely weathered granite, strongly weathered granite, and moderately weathered granite; among them, the thickness of silt and silty soil is large, totaling about 40 m.

Table 1: Geological Conditions

Category	Type of genesis	Stratigraphic code	Stratification code	Rockiness
Soil layer	Artificial fill layer	Q_4^{ml}	①1	Vegetal fill
			①2	Block and stone fill
	Sea-Land Interaction Phase sediment layer	Q_4^{mc}	②	Silt
			③	Silty soil
			④	Gravelly sand
	Residual soil layer	Q^{el}	⑤	Gravelly clayey soil
Rock formations	Yanshan III intrusive rocks	$\gamma_5^{2\text{-}3}$	⑥	Fully weathered granite
			⑦	Strongly weathered granite
			⑧	Mesothermal granite

Table 2: Recommended Design Parameters for Pre-cast Piles

Layer No.	Geotechnical Name	Geotechnical Condition	Characteristic Value of Pile End Resistance q_{pa} (kPa)		Characteristic Value of Pile Side Friction q_{sa} (kPa)	Negative Friction Coefficient k_0 tgφ	Pull-out Friction Resistance Reduction Coefficient λ_i
			Pile Penetration Depth (m)				
			$16 < L \leq 30$	$L > 30$			
①1	Vegetal fill	Uncompacted	/	/	10	0. 30	0. 65
①2	Block and stone fill	Uncompacted	/	/	12	0. 30	0. 60
②	Silt	flowing plastic	/	/	8	0. 20	0. 65
③	Silty soil	flowing plastic	/	/	10	0. 20	0. 65
④	Gravelly sand	slightly denser	/	/	35	/	0. 60
⑤	Gravelly Clay	Hard plastic	2700 (2900)	3100 (3300)	45	/	0. 70
⑥	Fully weathered Granite	Hard Plastic - Hard	5000 (5500)		100	/	0. 75
⑦	Strong weathering Granite	Semi-rocky and semi-earthy	6000 (6500)		-	/	0. 80

4.1.2 Foundation Design Information

(1) The foundation adopted prestressed high-strength concrete pipe-pile foundation, with a design grade of Class B. The model of pipe-pile is PHC-500 (AB)-125, with an outer diameter of 500 mm and a wall thickness of 125 mm. The characteristic value of the vertical bearing capacity of a single pile is 2000 kN (negative friction resistance of 300 kN).

(2) The pile foundation is constructed using the hydraulic hammer driving method, with a

hammer weight of 14 tons and a stroke of 500-800 mm. The designed effective pile length is 55 m, and the designed pile tip should penetrate the bearing layer for at least 6.0 m (completely weathered granite) or 1.5 m (strongly weathered granite). The final penetration depth is 10-20 mm.

(3) The concrete strength of the pile cap is C30, with a 100 mm embedment of the pile top into the pile cap. The height of the pile cap can be either 800 mm (single-pile cap) or 1200 mm (double-pile cap). The concrete strength of the cap-beam connecting beam is also C30 and the elevation of the beam is the same as that of the pile cap. The dimensions of the connecting beam are either 400 mm × 700 mm or 500 mm × 700 mm. The minimun span-to-depth ratio is 1/37, and the mid-span reinforcement of the connecting beam is supplementary reinforcement.

(4) After the construction of the pile foundation is completed, due to adjustments in the overall architectural planning layout, the building is shifted 300 mm to the right, resulting in a 300 mm offset between the centroid of the frame columns and the centroid of the pile cap, causing eccentric arrangement of the pile columns.

4.2 Field Testing

4.2.1 Pile Testing

According to the "Pile Testing Report" issued by the local construction project quality supervision and testing station, low-strain method testing and vertical compression static load tests were conducted on the piles after the completion of the pile foundation construction. The ultimate bearing capacity of the tested piles meets the design requirements, and the integrity categories of the pile shafts are classified as Category I and Category II.

4.2.2 Settlement and Tilt

(1) The overall settlement and displacement of the building are towards the northwest. The "triangular area" at the northwest corner (between grid lines 12-3 intersecting 12-D and 12-5 intersecting 12-B) is the most severely settled. Starting from November 23, 2021, the accumulated settlement at the CJ12-62 monitoring point is -179.06 mm, with a rate of -0.54 mm/d; the accumulated settlement at the CJ12-61 monitoring point is -113.92 mm, with a rate of -0.43 mm/d; the 12-D axis has shifted 40.8 mm to the north, the 1/12-3 axis has shifted 33.96 mm to the west, and the 12-5 axis has shifted 14.55 mm to the west. Figure 1 shows the layout of the foundation plan and settlement monitoring points.

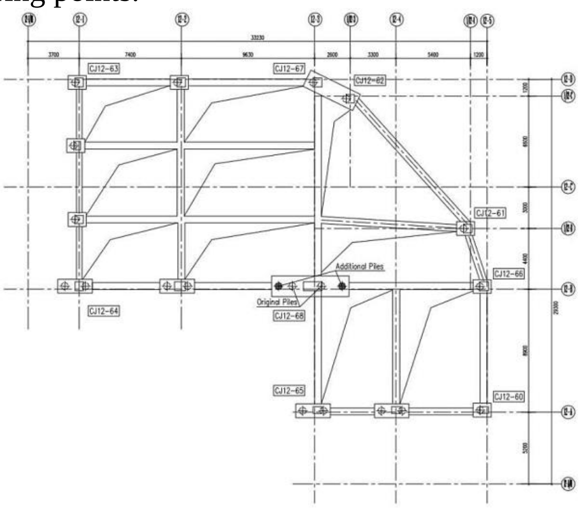

Figure 1: Layout of foundation plan and settlement measurement points

(2) As of March 8, 2021, the cumulative settlement of the main structure has reached 179.06 mm. The deformation rate in this period is relatively small, with an average settlement rate of 0.07 mm/d (compared to 0.03 mm/d in the previous period). The average settlement rate in the triangular area (CJ12-61, CJ12-62, CJ12-66, CJ12-67) is 0.5 mm/d (compared to 0.39 mm/d in the previous period), and the maximum differential settlement has reached 208.55 mm. The differential settlement between columns and the overall tilt of the building has exceeded the allowable limits specified in the regulations [5] (differential settlement is 0.002 times the distance between adjacent column measurement points, and overall tilt is 0.004). The foundation settlement is shown in Table 3.

Table 3: Foundation Settlement Record

Detection Time	23 November 2021	13 February 2022		8 March 2022	
Measurement points	Initial value	Cumulative	Rate of change	Cumulative	Rate of change
CJ12-60	4.26252	-69.43	-0.56	-76.71	-0.28
CJ12-61	4.38114	-101.21	-1.00	-113.92	-0.43
CJ12-62	4.12371	-165.28	-0.97	-179.06	-0.54
CJ12-63	4.62589	17.93	0.12	25.28	0.46
CJ12-64	4.71968	16.34	0.11	22.53	0.33
CJ12-65	4.69488	21.98	0.10	29.49	0.50
CJ12-66	4.69488	-37.24	-0.83	-49.26	-0.56
CJ12-67	3.95863	-38.40	-0.81	-50.45	-0.49
CJ12-68	4.00190	11.05	0.07	17.05	0.36

4.2.3 Structural and non-structural damage

Significant cracks have appeared in some connecting beams and the first-floor beams, with a maximum crack width of approximately 4 mm. The underground self-supporting masonry walls have experienced severe cracking and significant gaps with the bottom of the first-floor beams. The above-ground masonry walls show noticeable cracks, extensive detachment of the finishing layer, and severe cracking and detachment of ceramic tiles. Figure 2 and Figure 3 depict the on-site structural and non-structural component damage. Figure 2 shows the tension failure of the connecting beams, while Figure 3 shows the separation between the underground self-supporting masonry walls and the first-floor beams.

Figure 2: Tension Failure of Connecting Beams

Figure 3: Separation between Underground Self-Supporting Masonry Walls and First-Floor Beams

4.3 Settlement Analysis

4.3.1 Weak Lateral Constraint of Soil on Single Piles

Due to the conditions of the silty soil, the soil's constraint on the pile is weak. The lateral stiffness of the prestressed pipe-piles is relatively small. During construction, multiple segments of pipe-piles are often connected, making prestressed pipe-piles more prone to deformation and bending under vertical forces, resulting in the occurrence of second-order effects.

4.3.2 Excessive Length-to-Diameter Ratio of Piles

The specification[14] states that for prestressed pipe-piles used as end-bearing piles, the length-to-diameter ratio should not exceed 60. Additionally, when the piles pass through thick layers of soft soil, such as silt or potentially liquefiable soil, the stability of the pile shaft and its effect on bearing capacity should be considered. In this project, the designed pile lengths are close to 60 meters (length-to-diameter ratio of approximately 100), which does not meet the code requirements. Consequently, the piles are susceptible to buckling.

4.3.3 Weakness of Connecting Beams

The moments and shear forces at the column base are usually balanced by the foundation beams in that direction. Under the proper arrangement of the connecting beams, horizontal load-bearing capacity requirements for the piles are generally not necessary. According to the "Technical Code for Building Pile Foundations," adjacent foundation beams on the same axis should have longitudinal reinforcement extending between them[15].

In this project, the section height of the foundation beams is relatively small, and only stirrups are provided without longitudinal reinforcement. This results in a reduction in the necessary bond action of the foundation beams, making it difficult to balance the moments and shear forces at the column base. When slight settlement and displacement occur in the foundation, the foundation beams can be torn apart, leading to ineffective restraint of the settlement and displacement of the footings, ultimately resulting in larger settlement and displacement of the foundation.

4.3.4 Eccentricity between Column and Footing

Due to the eccentricity between the column and footing, besides the bending moment at the column base, there is an eccentric bending moment transmitted to the footing due to axial force at the column base. This has a more adverse effect on the prestressed pipe-piles beneath the footing. When the horizontal load-bearing capacity of the pile cannot resist the bending moment and shear forces from the footing, significant deformation or even failure of the piles may occur. Since the single pile foundation does not have a sufficient safety margin, any issues with the piles directly lead to settlement and displacement of the foundation.

The bending moment and shear force diagrams for a single pile foundation without eccentricity are shown in Figure 4, while the diagrams for a single pile foundation with eccentricity are shown in Figure 5. From these figures, it can be observed that the maximum values of pile bending moment, maximum positive shear force, and maximum negative shear force for a single pile foundation without eccentricity are 347 kN·m, 205 kN, and -108 kN, respectively. For a single pile foundation with eccentricity, the corresponding maximum values are 515 kN·m, 205 kN, and -156 kN, respectively. This demonstrates that the eccentricity between the column and footing increases the bending moment and shear forces on the piles, adversely affecting their performance.

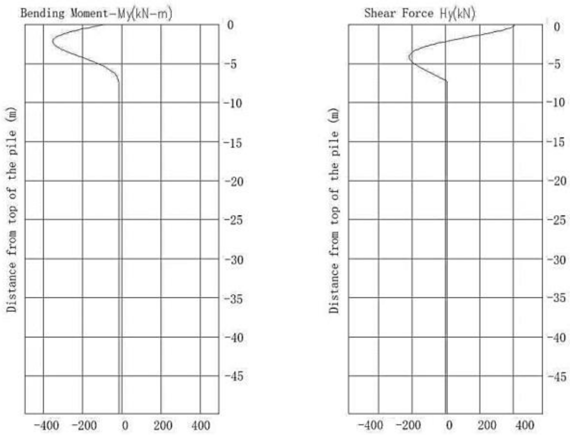

Figure 4: Bending Moment and Shear Force of a Column-Supported Single Pile Foundation under no Eccentricity Condition

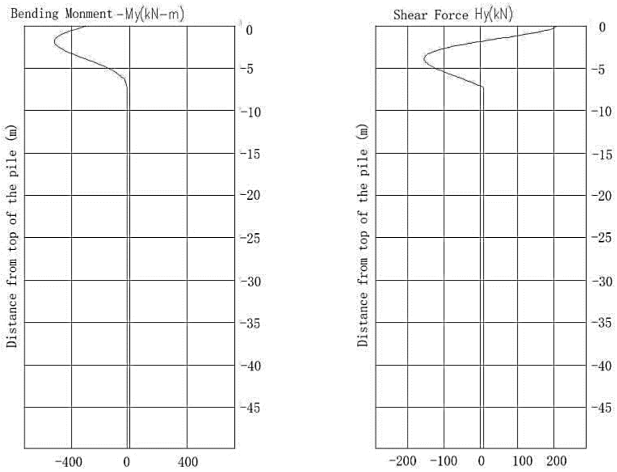

Figure 5: Bending Moment and Shear Force of a Column-Supported Single Pile Foundation under Eccentricity Condition

4.3.5 Impact of Construction Site Layout

There is a temporary construction road on the west side of the building, which serves as the passage for all heavy vehicles at the construction site. The repeated loading from the vehicle traffic increases the degree of consolidation settlement in the surrounding area of the temporary construction road, particularly in the soft soil layers. The settlement in the area of the D-axis pile foundation (near the temporary construction road) is greater than that in the A-axis and B-axis pile foundations. This results in uneven settlement with greater settlement on the west side of the building compared to the east side. Additionally, the unfilled cavity area on-site, which has not been backfilled to the design elevation, transfers part of the load generated by the height difference between the interior and exterior soil mass to the piles. The increased horizontal soil pressure and the effect of repetitive dynamic loading in the surrounding area contribute to some extent to the bending deformation of the piles. Figure 6 illustrates the location of the temporary construction road.

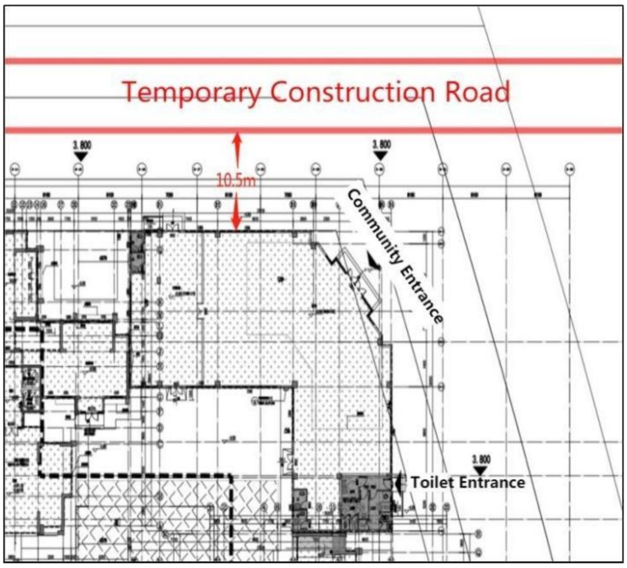

Figure 6: Illustration of the Location of the Temporary Construction Road

5. Conclusions and Prospects

The characteristics of silt and soft soil present unique challenges to the design and construction of foundation engineering. Prestressed pipe-piles have shown good load-bearing capacity and stability, making them an effective solution for addressing foundation settlement issues in soft ground. This study conducted an in-depth analysis of the foundation settlement problem in a coastal area of Guangdong Province, China, and identified several factors that may contribute to the settlement, including weak lateral constraint of soil on single piles, the excessive length-to-diameter ratio of the piles, weak connection beams, eccentricity between columns and footings, and the influence of construction site layout.

It should be noted that the research case in this study is based on a specific project in a coastal area of Guangdong Province, and the applicability of the findings may be limited by regional differences in geology, climate, and soil conditions. Future research could expand the sample size to include more cases from different geographic locations and engineering backgrounds to validate the generalizability of the research conclusions.

Considering the limitations of the current study and the need for further exploration, future research can focus on the following directions to enhance the application of prestressed pipe-piles in soft ground and provide more reliable technical support for related engineering practices:

(1) In-depth investigation of the application of prestressed pipe-piles in soft ground under different geographic locations and engineering backgrounds. By collecting more cases and conducting a systematic comparative analysis, the applicability of prestressed pipe-piles under different environmental conditions can be verified, and more universally applicable design and construction guidelines can be provided.

(2) Further optimization of the design methods for prestressed pipe-piles, including determining the pile length, diameter, and pre-stressing level. Through numerical simulation and field testing, the optimal design parameters can be explored, leading to more cost-effective design solutions for prestressed pipe-piles.

(3) Strengthening the long-term performance monitoring and evaluation of pile foundations, especially in soft ground. By conducting long-term observations and data analysis, the deformation, settlement, and load-bearing capacity of prestressed pipe-piles over time can be understood, providing more reliable guidance for engineering practices.

(4) Further exploration of the combined application of prestressed pipe-piles with other ground improvements techniques, such as diaphragm walls, ground anchors, and soil nails. By integrating different ground improvement methods, the overall stability and load-bearing capacity of soft ground can be enhanced.

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