Article │ Received 4 February 2025; Accepted 23 March 2025; Published 27 March 2025
https://doi.org/10.55092/pe20250002

Study on applicability of PC engineering pile in soft soil area of foundation pit in Wenzhou

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Abstract: According to the application of PC engineering pile for foundation pit support in Wenzhou silty soft soil area, although its construction convenience and construction speed are more prominent, but the lack of theoretical basis for safety, and the excavation displacement and deformation are often large and local collapse engineering accidents in Wenzhou soft soil area. In this paper, the applicability of PC engineering pile is studied through theoretical calculation and computer calculation compared with commonly used drilled pile, and finally, the typical foundation pit cases of Wenzhou actual engineering are compared and analyzed, which provides certain guiding significance and reference value for the support design of PC engineering pile in Wenzhou area in the later period.

Keywords: foundation pit support; PC engineering pile; mucky soft soil

1. Introduction

PC engineering composite steel pipe pile (referred to as PC engineering pile) is a composite supporting pile which adopts prefabrication and connects steel pipe pile with Larsen steel sheet pile by setting connecting small groove, as shown in Figure 1. With the development of green energy saving and prefabricated buildings [1], PC engineering pile has been widely used in the foundation pit supporting structure in Wenzhou due to its construction convenience [2]. As the soil in Wenzhou is mainly silty soft soil, the engineering mechanical properties are poor, and the foundation pit engineering accidents occur one after another, but whether it is caused by the safety of PC engineering pile. And it is urgent to study the applicability of PC engineering pile supporting structure in Wenzhou soft soil area [3].

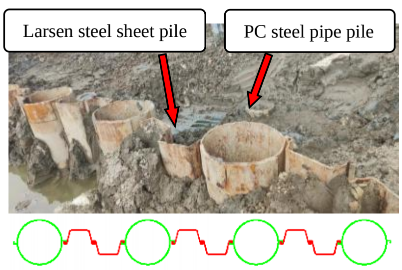

Figure 1. PC engineering pile diagram.

2. PC engineering pile theoretical calculation and comparative analysis of computer calculation

2.1. Theoretical calculation

Direct calculation of the strength of the PC engineering pile is not comparable, and the influence of the soil condition on the earth pressure is also different, so first of all, the bearing capacity and stiffness of the commonly used 600-diameter drilled pile and the main stress component of the PC engineering pile (hereinafter referred to as the PC steel pipe pile, the commonly used model is 630 mm in diameter and 14 mm in thickness) are theoretically compared. 600-diameter drilled pile has been used in Wenzhou single-layer basement more and generally through practice test its supporting capacity and stiffness can meet the requirements of single-layer basement support [4]. The following are from the bearing capacity limit state and normal use limit state to calculate and compare PC steel pipe pile and 600-diameter drilled pile.

Calculation of limit state of carrying capacity. The force in PC engineering pile is mainly borne by PC steel pipe pile, so the theoretical calculation only calculates the bending strength and shear strength of PC steel pipe pile itself [5]:

(1) The bending strength of the steel pipe pile of PC steel pipe pile should meet the following requirements:

$$\frac{M}{\gamma \cdot \mathrm{W}} \leq f \tag{1}$$

In the formula: M - pile bending moment; W - section modulus of pile body; γ - plastic development coefficient of section. Take the plastic development coefficient of cross section γ = 1.15, steel strength design value of 310 N/mm, then get PC steel pipe pile 630 × 14 section bending capacity:

$$M = W \times f \times \gamma = 1.273 \times 10^{9} \times 310 \times 1.15 = 4.54 \times 10^{11} N \cdot \mathrm{mm} \tag{2}$$

Then calculate the bending capacity of 600-diameter drilled pile section, referring to Yang Shenggui, Bin Yang [6] and Bao Guo Xia [7] *et al.* "Calculation of normal section bending capacity of circular section reinforced concrete pile", check the table to get 600-diameter drilled pile, reinforcement area of about 3000 mm^2, its bending capacity is 2.09 × 10^8 N/mm, By comparison, it can be seen that the bending capacity of 630 × 14 section of PC steel pipe pile is much higher than that of 600-diameter drilled pile section.

(2) The shear strength of PC steel pipe pile should comply with the following provisions:

$$\tau = \frac{V}{2 \cdot \mathrm{A}} \leq f_V \tag{3}$$

In the formula: V - pile shear; A - section area of pile body; f_v - design value of shear strength of steel. The design value of the shear strength of the steel is 180N/mm, then the shear capacity of the 630 × 14 section of the steel pipe pile is obtained:

$$V = f_V \times 2 \times A = 180 \times 2 \times 27079.36 = 9.75 \times 10^{6} N \tag{4}$$

In the calculation of the shear strength of the 600-diameter drilled pile section, according to the formula of the circular section shear strength obtained in Sri Hartati Dewi [8] and Tongyan Liu [9] *et al.* "Discussion on the Calculation method of the shear strength of the circular section Concrete Structure":

$$V_{\mathrm{ca1}} = V_c + V_s = \frac{3\pi r^2}{4} f_t + \frac{\pi A_{sv1} f_{yv}}{2s} \cdot D \cdot \sin a = 3.14 \times 10^{5} N \tag{5}$$

By comparison, it can be seen that the shear capacity of 630 × 14 section of PC steel pipe pile is also greater than that of 600-diameter drilled pile.

Calculation of limit state in normal use**.** Under the premise that the rest remains unchanged, the displacement change of supporting pile is mainly controlled by its own stiffness EI. The elastic modulus of concrete is taken as C25 of 2.8 $\times 10^4$ N/mm^2 (due to the small proportion of reinforcement, the elastic modulus of drilled pile can be basically replaced by concrete), then the stiffness of 600-diameter drilled pile is obtained:

$$E_1 I_1 = E_1 \cdot \frac{D^4}{64} = 5.67 \times 10^{13} \tag{6}$$

The elastic modulus of steel is 20.6 $\times 10^4$ N/mm^2 , and the stiffness of PC steel pipe pile is 630 × 14:

$$E_2 I_2 = E_2 \cdot \frac{D^4 - \mathrm{d}^4}{64} = 8.43 \times 10^{13} \tag{7}$$

In comparison, it can be found that the stiffness of 630 × 14 PC steel pipe pile (E_2I_2) is > 600-diameter drilled pile (E_1I_1), and the pile body displacement of PC steel pipe pile and drilled pile is compared by machine.

2.2. Straightening and comparing of machine calculation

This computer calculation adopts Lizheng deep foundation pit 7.0 two-dimensional unit calculation software, and the soil mass adopts Wenzhou conventional soft soil. The soil parameters are as follows: heavy r = 16 KN/m^3; C = 7.0, φ = 6.0, depth 30 m, silt horizontal resistance factor m = 1.0, underground water level buried depth 1.0 m, and uniform load 15 kpa is considered outside the pit. Pile rows with different depths of 4 m, 4.5 m, 5 m, 5.5 m and 6.0 m (pile spacing of 1.5 m and pile length of 14 m) plus internal support system, as well as PC engineering pile corresponding to cantilever support system and 600-diameter drilled pile were compared for pile body displacement. The calculation model in shown in Figure 2 and Figure 3. The calculation results are shown in Table 1:

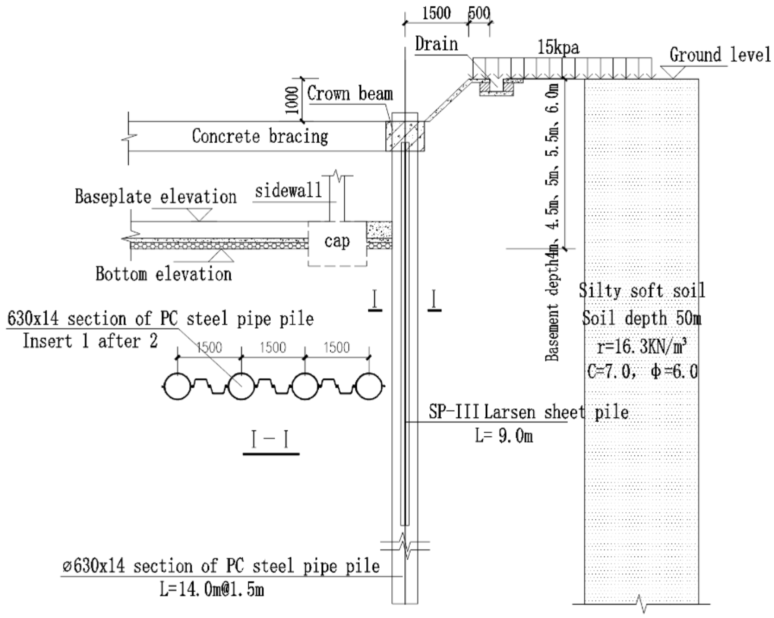

Figure 2. Calculation model of pile row plus internal support.

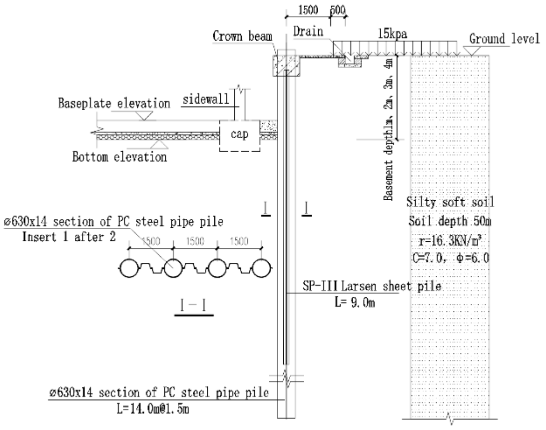

Figure 3. Calculation model of cantilever support.

Table 1. Comparison of pile body displacements of pile rows + internal supports at different calculation depths.

Calculation of digging depth (pile row + internal support)	PC engineering pile/mm	drilled pile /mm	Compare results
4 m	29.15	32.92	Under the same digging depth, the Maximum displacement PC engineering pile is smaller than the drilled pile.
4.5 m	35.67	40.61	
5 m	43.40	49.81	
5.5 m	52.55	60.82	

In Table 2 below, the cantilever support system is used to compare PC engineering piles and 600-diameter drilled piles corresponding to different depths of 1.0 m, 2.0 m, 3.0 m and 4.0 m (pile spacing of 1.5 m and pile length of 12 m).

Table 2. Comparison of pile body displacement of cantilever support with different calculation depths.

Calculation of excavation depth (cantilever pile support)	PC engineering pile /mm	drilled pile /mm	Compare results
1.0 m	6.33	6.89	Under the same digging depth, the maximum displacement PC steel pipe pile is smaller than the drilled pile
2.0 m	13.09	14.04	
3.0 m	22.14	23.98	
4.0 m	34.48	38.01	

As can be seen from Table 1 and Table 2 above: The calculation results under the same digging depth, whether it is a row pile plus internal support or cantilever support system, the maximum displacement of PC engineering pile is smaller than that of drilled pile, and the theoretical calculation of support stiffness PC engineering pile is larger than drilled pile, which corresponds to and conforms to the law that the larger the support stiffness is, the smaller the control displacement. However, 600-diameter drilled piles have been generally tested in single-storey basements in soft soil areas and their support stiffness can meet the design requirements [10].

Through the comparison results of the above theoretical calculation and computer calculation, it can be concluded that PC engineering pile used in ordinary single-storey basement can meet the design and use requirements in terms of bearing capacity and displacement control during the excavation stage.

3. Comparative analysis of actual engineering cases

3.1. Project overview

An equipment plant in Wenzhou is located in Yueqing City, Wenzhou. The north side of the surrounding environment is 12.7 meters away from the pit side, and the other three sides are open land. The size of the foundation pit is about 49 m × 24 m, as shown in Figure 4 and Figure 5. The safety grade of the foundation pit of this project is Ⅱ, the importance coefficient is 1.0, the foundation form is pipe pile foundation, and the excavation depth from the basement foundation pit to the bottom of the basement floor is 5.25 m.

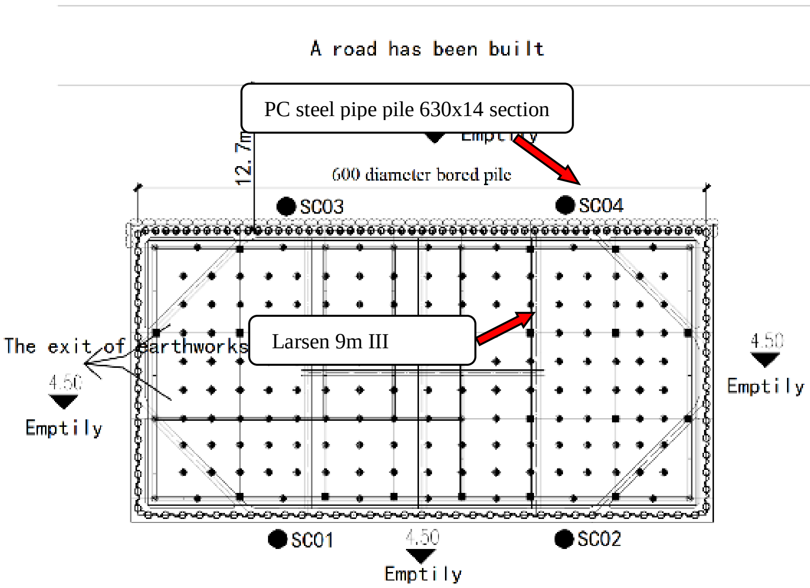

Figure 4. Foundation pit supporting plane layout.

Figure 5. Real scene map of PC engineering pile on site.

3.2. Soil condition

According to the geotechnical investigation report, as shown in Table 3, the soil layer in the influence range of foundation pit excavation depth from top to bottom is: ①$_0$ miscellaneous fill, ②$_1$ silt. ①$_0$ miscellaneous fill: mixed color, loose–slightly dense, after investigation, the filling time is recently artificial backfill, without rolling compaction treatment, the layer thickness of 1.50–7.00 m.; ②$_1$ Silt: cyan gray, flow plastic, high compressibility, high sensitivity, layer thickness 17.80–35.40 m, the holes are distributed. The influence area of foundation pit is mainly pore diving.

Table 3. Main mechanical parameters of rock and soil.

Soil layer	Water content W (%)	Natural weight gamma (kN/m3)	Consolidation fast shear strength indicator	
			Cohesion C (kPa)	Internal friction Angle φ (°)
①$_0$ miscellaneous fill	--	(18.0)	(5.0)	(10.0)
②$_1$ Silt	70.2	15.37	8.8	7.7

Note: c, φ values are consolidation fast shear peak index; The values in ( ) are empirical values.

3.3. Comparison of foundation pit scheme and monitoring data

Considering the requirements of the local foundation pit management documents, the north side of the vertical envelope structure adopts 600 mm-diameter drilled cast-in-place piles with 800 mm spacing and 16 m length as well as biaxial mixing piles for water sealing, and the remaining three sides adopt the PC engineering pile support (the bearing steel section is 16m steel pipe pile model 630 × 14 mm, the spacing is 1.5 m, and 9 m Larsen steel sheet piles are arranged in the middle). The horizontal support adopts the support form of reinforced concrete internal support. Because the north road does not actually take heavy vehicles, and there is an open space between the north road and the foundation pit, it is considered that the load on both sides of the foundation pit is basically the same. The construction period of the foundation pit in this project is about 63 days from the excavation to the completion of the floor pouring, and the monitoring data of the first, 30th and 63rd days of excavation are taken as the time nodes. Deep soil horizontal displacement monitoring points SC01 and SC02 correspond to PC engineering pile support, SC03 and SC04 correspond to drilled pile support, and the monitoring data are shown in Figure 6, Figure 7 and Figure 8 below:

In Figure 6, the first day of foundation pit excavation to the bottom of the bottom, the displacement of the PC engineering pile is greater than that of the drilled pile, because the gap around the assembled support body and the deep measurement pipe may be squeezed by the soil, so it can be seen from the horizontal displacement data of the deep soil that the deformation displacement of the PC engineering pile is greater than that of the drilled pile.

In Figure 7, the 30th day of foundation pit excavation to the bottom of the bottom, the maximum horizontal displacement of the deep soil of the SC01 and SC02 points corresponding to the PC engineering pile is 29.55 mm and 44.96 mm respectively, which is greater than that of the SC03 and SC04 points corresponding to the drilled pile support is 19.50 mm and 21.75 mm respectively. In Figure 8, after the bottom plate is poured on the 63th day, the maximum horizontal displacement of the deep soil of the SC01 and SC02 points corresponding to the PC engineering pile is 44.91 mm and 51.88 mm, which is still greater than that of the SC03 (maximum 39.29 mm) and SC04 (maximum 35.85 mm) points corresponding to the drilled pile. The horizontal displacement of the deep soil obtained in the actual project is not in accordance with the above theory and the conclusions obtained by computer calculation. In fact, the soil uplift phenomenon in the pit is more serious in the process of the three-sided excavation of the PC engineering pile (as shown in Figure 9), and the soil uplift phenomenon is smaller when the support side of drilled pile is excavated than that of PC pile. The reasons are mainly that the spacing of the long 16m PC steel pipe pile in the PC engineering pile is 1.5 m, and the middle is a short 9 m Lassen steel sheet pile [11]. Because the flow plasticity of the silty soil is large, part of the silty soil bypasses the bottom of the Lassen steel sheet pile and flows into the pit, resulting in uplift and damage.

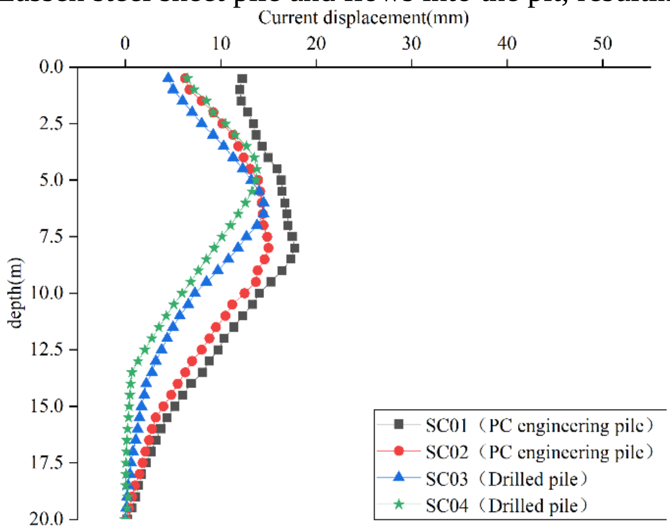

Figure 6. pit excavation to bottom (Day 1).

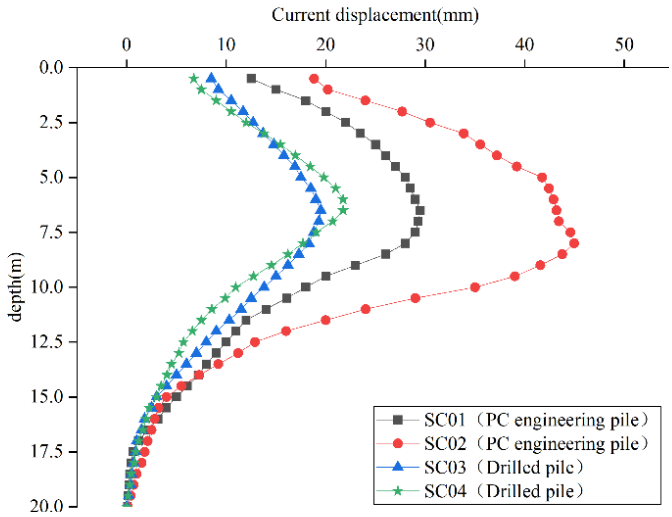

Figure 7. pit excavation to bottom (Day 30).

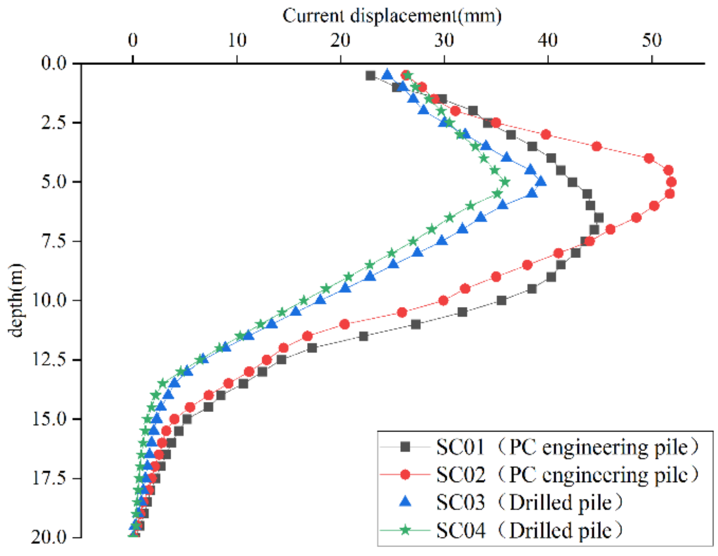

Figure 8. pit excavation to bottom (Day 63).

Figure 9. Uplift in foundation pit.

In fact, a number of practical engineering cases in Wenzhou can prove that in the foundation pit engineering in silty soft soil, the phenomenon of pit uplift is more or less common. The maximum displacement of PC engineering pile in the above engineering is 51.88 mm at SC02 point, which is still within the reasonable range of foundation pit deformation [12]. From Figure 6, Figure 7 and Figure 8, the following conclusions can be drawn: the horizontal displacement of deep soil supported by PC engineering pile is within a reasonable range, and the PC engineering pile support can meet the requirements of the general single-storey basement support engineering in Wenzhou soft soil area for the control and protection of surrounding environmental displacement. However, it is suggested to increase the length of Lassen steel sheet pile in the PC engineering pile to prevent the pit uplift from becoming more serious.

4. Conclusion

Through the research of PC engineering pile in the field of foundation pit support in Wenzhou soft soil area, the applicability of PC engineering pile in Wenzhou area is analyzed from the perspective of theoretical calculation, theoretical and mechanical comparison and practical engineering cases. The following conclusions are drawn:

(1) Through the comparison of theoretical calculation and theoretical and mechanical calculation, the commonly used PC engineering pile is 630 × 14 steel pipe pile, whose bearing capacity and stiffness are greater than 600-diameter drilled pile. It can meet the design and use requirements of foundation pit support for single-storey basement in soft soil area.

(2) Through the comparison of practical engineering data between PC engineering pile and drilled pile, it is concluded that the horizontal displacement of deep soil body supported by PC engineering pile is within a reasonable range. PC engineering pile support can meet the requirements of general single-storey basement support engineering in Wenzhou soft soil area for the control and protection of surrounding environmental displacement. But it is suggested to increase the length of Lassen steel sheet pile in PC engineering pile to prevent the serious uplift phenomenon in the pit.

Acknowledgment

Fund Project: Wenzhou Science &Technology Bureau (S2023028), Wenzhou Polytechnic (WZY2024011).

Conflicts of interests

The authors declare no conflict of interest.

Authors' contribution

Conceptualization, Feng Cai; methodology, Feng Cai; software, Yu Liu; validation, Xiaofang Ma and Qingling Wu; formal analysis, Yu Liu; investigation, Feng Cai; resources, Feng Cai; data curation, Yu Liu; writing—original draft preparation, Feng Cai; writing—review and editing, Xiaofang Ma and Qingling Wu; visualization, Yu Liu; supervision, Yu Liu; project administration, Feng Cai; funding acquisition, Feng Cai. All authors have read and agreed to the published version of the manuscript.

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