Research on advantages and disadvantages of prestressed concrete hollow square pile and pipe pile in pile foundation selection

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Abstract. In the process of industrial plant construction, pile foundation selection has a direct impact on the structural design. It is the goal of construction, design, investigation, supervision and construction units to find a pile type that can meet the economic rationality and quality requirements, and is conducive to construction and reduce the impact on the surrounding environment and buildings. In this paper, combined with the pile foundation selection design of the industrial plant, through the field investigation, pile bearing capacity detection and investigation report analysis, the cost comparative analysis is completed, and the advantages and disadvantages of hollow square pile and pipe pile in design and construction are compared.

1. Introduction

1.1. Research background
With the continuous development of China's transportation, the economy of coastal and riverside areas is constantly improving, besides the number of new and expansion projects in economically developed areas is also increasing. Today, due to the limitations of geological conditions, many types of pile foundations have been added to make up for the defects of geological conditions, so as to meet the needs of completing all kinds of engineering construction on soft soil foundation.

The early primitive wooden pile, after development, in the early 19th century, began to appear cast iron sheet pile, and then to the middle of the 19th century, with the emergence of cement industry, reinforced concrete began to be applied to the lower structure of engineering construction, and constantly optimized. Until the early 20th century, with the rapid development of pile making technology, various forms of precast piles were used as pile foundation in various projects.

In many types of pile foundation, prestressed concrete pile is widely used in today's engineering. In the case of little difference in project cost, the construction speed is fast and the vertical bearing capacity is large. Due to the use of shaped steel formwork for prefabrication in the processing plant, the quality has been greatly guaranteed, which can not only meet the geological requirements, but also meet the rapid development trend. Compared with cast-in-place bored pile, its disadvantages are more and more obvious.

However, as a prestressed concrete pile, due to different cross-section shape and bearing capacity, the design size and reinforcement amount of foundation cap are also affected differently.
Among them, prestressed concrete pipe pile in a large number of engineering applications and practices, because of its circular section, smooth appearance, when used as friction pile, small friction with soil and other shortcomings gradually exposed, many projects need to use larger pipe diameter pipe pile, or use solid square pile, but it also increases the cost of the project. Therefore, in the engineering application, the prestressed concrete solid square pile is gradually made into hollow, in order to reduce its engineering cost. Prestressed concrete hollow square pile mainly comes from the optimization products of prestressed concrete solid square pile and pipe pile. Therefore, in the selection of pile foundation, under the premise of meeting the quality of engineering structure, the project comprehensive cost is an extremely important reference basis in the selection of pile foundation.

1.2. The purpose and significance of the research
When all kinds of engineering structures adopt pile foundation, the engineering cost of foundation and foundation part is generally large, accounting for a considerable proportion of the overall project investment. Different types of pile foundation, corresponding to different foundation structures, produce different amounts of reinforcement and concrete. Therefore, it will cause the change of project cost.

This paper compares and analyzes the advantages and disadvantages of prestressed concrete hollow square pile and pipe pile from four aspects: material cost of pile foundation, bearing capacity, size of superstructure (foundation cap) and reinforcement amount, then obtains the relatively economic and reasonable pile type. It can reduce the calculation amount of prestressed concrete pile selection in the future construction of all kinds of buildings, and provide a strong reference for the pile foundation design and selection of similar construction projects.

1.3. Research method
The research methods of this paper are literature research, field investigation and comprehensive evaluation.
- By studying the basic theory and construction technology of building pile foundation at home and abroad, this paper systematically expounds the basis of pile foundation selection.
- Through the field investigation, the actual pile end bearing capacity and static load test data of prestressed concrete hollow square pile and pipe pile are compared and analyzed. The influence of different pile type design drawings on reinforcement and concrete quantity of independent bearing platform foundation is studied, which provides technical basis for pile foundation selection.
- Through the comprehensive evaluation of various factors such as the production situation of different pile types and material prices, the type of pile foundation selection is finally achieved.

2. A summary of the current situation at home and abroad

2.1. Introduction of prestressed concrete pile
Prestressed concrete piles are divided into pipe pile, solid square pile, hollow square pile, special-shaped pile and so on according to different cross-sections. The cost of solid square pile and special-shaped pile is high, which can not achieve good economy. Because the center of hollow square pile and pipe pile is hollow, the amount of concrete and reinforcement is less, the cost is relatively low, and the economy is better.

The advantages of prestressed concrete hollow square pile and pipe pile are mainly reflected in the following three aspects:

2.1.1. Good mechanical properties. The concrete used in prestressed concrete pile is not less than C80, which belongs to high strength concrete. The yield strength is about 1500MPa, and the diameter is less than 1400mm. The strength of pile body and the bearing capacity of single pile are relatively large,
which can meet the demand of large bearing capacity with relatively small diameter specification. The pile diameter classification is shown in Table 1.

| Pile type                              | Side length / pile diameter type (mm) | Design value of vertical compressive bearing capacity (KN) |
|----------------------------------------|--------------------------------------|----------------------------------------------------------|
| Prestressed concrete hollow square pile (take AB type pile as an example) | 300                                  | 1864                                                     |
|                                        | 350                                  | 2496                                                     |
|                                        | 400                                  | 3000                                                     |
|                                        | 450                                  | 4105                                                     |
|                                        | 500                                  | 4891                                                     |
|                                        | 550                                  | 5526                                                     |
|                                        | 600                                  | 6195                                                     |
|                                        | 650                                  | 7714                                                     |
|                                        | 700                                  | 9154                                                     |
| Prestressed concrete pipe pile         | 300                                  | 1271                                                     |
| (take AB type pile as an example)      | 400                                  | 2288                                                     |
|                                        | 500                                  | 3158                                                     |
|                                        | 600                                  | 4255                                                     |
|                                        | 700                                  | 5124                                                     |
|                                        | 800                                  | 5992                                                     |
|                                        | 1000                                 | 8929                                                     |
|                                        | 1200                                 | 12434                                                    |

2.1.2. The production speed is fast. Prestressed concrete hollow square pile and pipe pile are prefabricated by processing plant, and produced by high temperature, high pressure, autoclave and other modern technologies, which greatly shortens the production cycle, and can be completed within 24 hours from customized processing to transportation into the construction site.

2.1.3. High construction efficiency. At present, the most commonly used construction machinery is static press, which has low noise and fast construction speed. A static press can complete the static pressure construction of 50 ~ 60 prestressed concrete piles every day. The construction process is simple, which can not only meet the environmental protection requirements of no dust and low noise, but also shorten a lot of construction period.

2.2. Current situation at home and abroad

In today's world, Japan is the country with the most in-depth research, the most advanced technology and the most use of pipe piles, the market share of pipe piles is up to 50%. However, after the United States put forward the relevant design and processing regulations of concrete pile in 1973, it began to produce prestressed concrete solid square pile and hollow square pile on a large scale, and continued to apply and practice in highway, port and other places.

In the 1980s, at the beginning of the national reform and opening up, coastal areas began to vigorously develop the economy, but its various types of soft soil foundation is not suitable for the construction of high-rise buildings, so began to introduce concrete pipe pile. Slowly, with the continuous improvement of China's specifications and the continuous innovation of science and technology, prestressed concrete square pile is gradually derived, with larger surface area and greater side friction, which is more competitive compared with pipe pile.
2.3. Summary
To sum up, the prestressed concrete hollow square pile has some advantages over the pipe pile in quality, and the development trend is gradually approaching to the prestressed concrete hollow square pile. Nowadays, prestressed concrete hollow square pile has been used in various projects.

3. Comparison and selection of pile foundation design schemes for industrial plant

3.1. Project overview

3.1.1. General situation of engineering design. The proposed industrial project in Henan Province is adjacent to the urban trunk road in the south, the power plant in the west, and farmland in the East and North. The total construction area of the project is 78045.1 m², and the details of the proposed main buildings are shown in the table below:

| NO. | Building name                 | Building area (m²) | Cornice height (m) | Structural style   |
|-----|-------------------------------|-------------------|-------------------|-------------------|
| 1   | Comprehensive processing workshop | 60568.6         | 21.98             | Light steel / frame |
| 2   | Boiler room and water pump room | 2300.76          | 6.85              | frame             |
| 3   | Sewage treatment plant         | 3699.42          | 6.5               | frame             |
| 4   | Dormitory                     | 9234.14          | 10.25             | frame             |
| 5   | Canteen                       | 2242.18          | 22.2              | frame             |

The total construction period of the project is 360 calendar days, of which the planned construction period of pile foundation is 60 calendar days.

3.1.2. General situation of engineering site geology. According to the results of drilling, static cone penetration test and geotechnical test, the stratum is divided into 8 unit layers within the exploration depth. The detailed description of the geotechnical characteristics of each layer from top to bottom is as follows:

- **Layer 1: silty clay (Quaternary alluvium)**
  It is yellowish brown, soft plastic to plastic, slightly glossy, medium dry strength, medium toughness, containing a small amount of calcareous nodules, partially mixed with thin layer of silt, and cultivated soil above 0.5m. This layer is widely distributed.

- **Layer 2: silty clay (Quaternary alluvium)**
  It is yellowish brown, soft plastic to plastic, slightly glossy, medium dry strength, medium toughness, with yellow rust infection, occasionally calcareous nodules, locally mixed with thin layer of silt. This layer is widely distributed.

- **Layer 3: silty clay (Quaternary alluvium)**
  It is yellowish brown, soft plastic plastic, slightly glossy, medium dry strength, medium toughness, with a small amount of calcareous nodules and a thin layer of silt locally. This layer is widely distributed.

- **Layer 4: silty clay (Quaternary alluvium)**
  Brown yellow, soft plastic plastic, slightly glossy, medium dry strength, medium toughness, with yellow rust infection, occasionally calcareous nodules, locally mixed with a thin layer of silt. This layer is widely distributed.

- **Layer 5: silty soil (Quaternary alluvium)**
  Gray brown, wet, medium dense, no luster reaction, low dry strength, low toughness, moderate shaking response, with gray bands and yellow rust infection, yellow patches, local calcium nodules are rich, calcium nucleus particle size is about 0.5-2.0cm, locally mixed with silty clay. This layer is widely distributed.
- **Layer 6: silty clay (Quaternary alluvium)**
  It is yellowish brown, grayish brown, soft plastic to plastic, slightly glossy, medium dry strength, medium toughness, with gray spots, occasionally with calcareous nodules and partly with silt. This layer is missing locally.

- **Layer 7: silty clay (Quaternary alluvium)**
  Brown yellow, soft plastic plastic, slightly glossy section, no shaking reaction, medium dry strength, medium toughness, with gray spots and rust yellow spots, occasionally with calcareous nodules, locally with thin layer of silt. This layer is widely distributed.

- **Layer 8: silty soil (Quaternary alluvium)**
  It is yellowish brown, brownish yellow, medium dense dense, wet, no luster reaction, low dry strength, low toughness, moderate shaking response, with grayish yellow stripes, black ferromanganese oxide spots, local calcareous nodules are rich, the particle size of calcium nucleus is about 0.5-2.0cm, and locally mixed with silty clay layer. This layer is not exposed within the exploration depth.

| Table 3. Statistics of thickness, buried depth and bottom elevation of underground layers in the site |
|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| NO.   | Thickness (m) | Bottom buried depth (m) | Bottom elevation (m) |
|-------|---------------|-------------------------|----------------------|
|       | Min  | Max  | Ave  | Min  | Max  | Ave  | Min  | Max  | Ave  |
| 1     | 1.20 | 2.60 | 1.72 | 1.20 | 2.60 | 1.72 | 43.23 | 44.58 | 44.03 |
| 2     | 3.50 | 5.40 | 4.40 | 5.50 | 6.80 | 6.12 | 38.82 | 40.28 | 39.63 |
| 3     | 1.70 | 3.20 | 2.45 | 7.80 | 9.10 | 8.57 | 36.70 | 37.87 | 37.18 |
| 4     | 0.40 | 1.20 | 0.77 | 8.60 | 9.90 | 9.35 | 35.91 | 37.07 | 36.41 |
| 5     | 2.30 | 7.30 | 5.25 | 13.80 | 16.70 | 15.48 | 29.05 | 32.00 | 30.27 |
| 6     | 0.40 | 3.50 | 1.21 | 10.70 | 14.00 | 12.06 | 31.78 | 35.20 | 33.74 |

The main soil in this area is silt and silty clay, which is basically in the state of soft plastic to plastic, low strength, and contains a certain amount of organic matter, belonging to the typical soft soil foundation. Improper treatment of this kind of foundation will bring great quality and safety risks to the project. When building buildings, the selection of pile type needs to be careful to meet the bearing capacity requirements of the above ground structure.

3.1.3. **Hydrological survey of the project site.** According to the survey report of the project, the groundwater level is 3.1-3.5m below the ground (the absolute elevation is about 42.6m), and the ground elevation of the site is 45.3m relative to the absolute elevation. According to the regional hydrogeological data, the annual variation of groundwater level in this area is about 1.5m, which belongs to phreatic water type and is mainly supplied by atmospheric precipitation. According to the local long-term hydrological observation data, the local groundwater level has little change in recent 3-5 years.

Combined with the data of nearby sites, it is suggested that the design water level of anti-floating of the project can be about 45.6m in absolute elevation. According to the soluble salt analysis test of soil samples taken from the site, the results are shown in Table 4.

| Table 4. Analysis results of soluble salts in soil samples |
|----------------------------------------------------------|
| Project | $K^+Na^+$ | $Ca^{2+}$ | $Mg^{2+}$ | Cl | $SO_4^{2-}$ | $HCO_3^-$ | $CO_3^{2-}$ | PH value |
|---------|-----------|-----------|-----------|-----|-------------|-----------|-----------|----------|
| 68-1    | 103.58    | 81.04     | 34.71     | 112.63 | 189.67     | /         | /         | 8.08     |
| 17-2    | 115.04    | 71.52     | 23.13     | 86.65 | 144.00     | /         | /         | 8.19     |

Note: The unit of $HCO_3^-$ is mmol / kg.

According to the analysis data of soluble salt in soil, the foundation soil has slight corrosivity to the reinforcement and concrete in reinforced concrete structure.
3.2 Preliminary comparison and selection of pile foundation schemes
As the project is an industrial project with large single pile load and large equipment foundation and other components, there are extremely high requirements for the bearing capacity and uplift resistance of the pile foundation. According to the survey report and combined with the geological and hydrological conditions of the site, the design unit puts forward two schemes for the pile foundation of the project: prestressed concrete hollow square pile and prestressed concrete pipe pile.

Table 5. Comparison of material parameters between prestressed concrete hollow square pile and pipe pile

| Material parameters                                      | Prestressed concrete hollow square pile (PHS300AB) | Prestressed concrete pipe pile (PHC400AB) |
|---------------------------------------------------------|--------------------------------------------------|------------------------------------------|
| Diameter (side length)                                  | 300mm                                           | 400mm                                    |
| Wall thickness (inner diameter)                         | 160mm                                           | 95mm                                     |
| cost                                                    | 180RMB/m                                        | 180RMB/m                                 |
| Surface area                                            | 14.4m²                                          | 15.07m²                                  |
| Internal surface area                                   | 6.03m²                                          | 7.91m²                                   |
| Sectional area                                          | 69904mm²                                        | 90981.5mm²                               |
| Effective preloading stress of concrete                 | 5.48N/mm²                                       | 6N/mm²                                   |
| Design value of vertical compressive bearing capacity   | 1864kN                                          | 1752kN                                   |

Compared with prestressed concrete pipe pile, the cost of prestressed concrete hollow square pile is the same, and the theoretical bearing capacity is larger. When it is also used as the pile foundation of the comprehensive processing workshop, through the preliminary design, the detailed drawings of the independent bearing platform above the two pile foundations are as follows:

3.2.1 Design details of two pile caps (prestressed concrete pipe pile).
3.2.2 Design details of two pile caps (prestressed concrete pipe pile).

Figure 1. Design details of two pile caps (prestressed concrete hollow square pile).

(a) Plan

(b) Section A-A

(c) Section 2-2

Figure 2. Design details of two pile caps (prestressed concrete hollow square pile)
3.2.3. The comparison of two different pile types corresponding to independent bearing platform foundation is shown in Table 6.

| Design parameters | Prestressed concrete hollow square pile (PHS300AB) | Prestressed concrete pipe pile (PHC400AB) |
|-------------------|---------------------------------|---------------------------------|
| Height of bearing platform | 800mm | 800mm |
| Plane dimension | 1650mm×600mm | 2200mm×800mm |
| ① No.1 steel bar | 7 HRB400E, diameter 20mm | 4 HRB400E, diameter 20mm |
| ② No.2 steel bar | 6 HRB400E, diameter 20mm | 4 HRB400E, diameter 20mm |
| Reinforcement amount of independent bearing platform foundation | 85.98kg | 120.70kg |
| Concrete quantity of independent bearing platform foundation | 0.792m³ | 1.408m³ |

According to the characteristics of the pile foundation and the design scheme of the corresponding independent bearing platform foundation, the safety and quality are the premise. Considering the cost, the amount of reinforcement and concrete in the prestressed concrete hollow square pile foundation structure is less, and the economy is better.

3.3. Static pressure comparison and selection of pile foundation on site

Considering that there are many factors affecting the selection of pile foundation, the actual static pressure construction of prestressed concrete piles is carried out on site, with 4000 square piles and 400 pipe piles. The static pressure data of the same pile type has no significant change. The actual static pressure data show that 100 prestressed concrete piles are selected as examples, as shown in figure 3 and figure 4.

Figure 3. Actual pile pressing force curve of prestressed concrete hollow square pile and pipe pile

Figure 4. Pressure gauge number curve of prestressed concrete hollow square pile and pipe pile
Through the detection of the characteristic value of vertical compressive capacity of single pile, the results meet the design requirements $r_a=600\text{kn}$. The test process is loaded in different stages. The graded load is $1/10$ of the design ultimate bearing capacity, and the first stage is twice the rated load. The maximum load is $1200\text{kN}$. See Table 7 for specific classification.

| Classification | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|----------------|----|----|----|----|----|----|----|----|----|
| Load (KN)      | 240| 360| 480| 600| 720| 840| 960| 1080| 1200|

Through the analysis of the above situation:

- Firstly, from the perspective of cost, the cost of prestressed concrete hollow square pile (phs300-ab) and pipe pile (phc400-ab) is the same, but the design reinforcement and concrete quantity of the corresponding independent bearing platform foundation are quite different, and the comprehensive cost of prestressed concrete hollow square pile is low.
- Secondly, from the aspect of material supply, at present, the usage of prestressed concrete hollow square pile in Henan market is small, and it has not been widely used. The prefabrication mold of hollow square pile is seriously insufficient, and there is no inventory. The production capacity of first-line manufacturers can only reach 50 ~ 60 pieces/day, which can not meet the demand of mass production in the short term, so it needs to wait for the manufacturer to allocate the prefabrication mold. Due to the large usage of prestressed concrete pipe piles, all manufacturers have stocks, and the prefabricated molds are sufficient, which can meet the construction needs.
- Thirdly, from the aspect of construction period, the static pressure method is adopted in the construction of the two types of piles, with the same static pressure machine and the same construction speed.
- In summary, although the prestressed concrete pipe pile has great advantages from the construction period, considering the project cost, the comprehensive construction cost of prestressed concrete pipe pile is higher, and the pile type of comprehensive processing workshop is prestressed concrete hollow square pile.

4. Analysis of implementation effect

According to the final results, the design unit carries out the structural design of the comprehensive processing workshop according to the prestressed concrete hollow square pile, and the overall project cost is saved by more than one million. The square pile manufacturers allocate molds from all over the country to produce prestressed concrete hollow square piles. Two static presses work at the same time on the construction site, working 20 hours a day. The pile foundation construction officially starts on the site in August 2020, and the static pressure of 4000 hollow square piles in the comprehensive processing workshop is completed by October 2020.

In the construction process, the supply of hollow square pile is relatively timely, the quality meets the design requirements, the static pressure process is very smooth, and there is no under delivery, pile head explosion and other phenomena. In the urban area with high environmental protection requirements, the construction method of no dust and low noise has not received any complaints during the whole project implementation period.

Economically speaking, it meets the owner's investment estimation and does not occupy the construction period. The construction period of the formal pile foundation is only ten days behind the original plan. The pile foundation construction is smooth, and the factory will be put into operation on time, providing employment opportunities for the society earlier, which has produced good economic and social benefits.

5. Conclusion and Prospect

In recent years, with the continuous development of the city to the suburbs, coastal areas, along the river and other edge areas, prestressed concrete piles have been used in all kinds of projects, in which
the number of pipe piles selected as pile foundation is large, and the number of pipe pile manufacturers in the country increases. But there is no real comparison of the comprehensive project cost between different prestressed concrete pile types. Through the comparison and selection of this project, it has great significance and value for the practical application of prestressed concrete hollow square pile. Through the performance analysis of the actual construction of pile foundation, it is found that the hollow square pile has higher bearing capacity and can save the material consumption of the foundation structure when the side length of the hollow square pile is similar to the diameter of the pipe pile and the project cost is the same, which verifies the economic advantages of this type of pile. If the processing mold of prestressed concrete hollow square pile can meet the production demand, it will also have great advantages in the construction period.

This paper provides a more objective evaluation for the comparison between prestressed concrete hollow square pile and pipe pile. If there are more quantifiable indexes, the selection result will be more accurate.

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