Construction technology of high-rise pile cap foundation of offshore wind power in Taiwan Strait

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Abstract. Offshore wind farms promise to become an important source of energy in the near future. The high-rise pile cap foundation is one of the typical foundation types for offshore wind turbine. This paper introduces the structural characteristics and construction technology of high-rise pile cap foundation, aiming at the characteristics of the sea area of Taiwan Strait and combining with engineering examples. The construction technology of high-rise pile cap foundation is expounded emphatically from the manufacture and transportation of steel pipe piles, pile foundation construction and bearing platform construction. Compared with the traditional construction technology, the construction technologies used in this project are safer and more reliable. The construction period of piles cap foundation is shortened by 10 ~ 48 days. The construction technology provides reference for offshore wind power foundation construction.

1. Introduction

In the globalized market, wind power has been considered as the most competitive price advantage of green energy technology, while leading the global energy transformation [1]. The total installed capacity of global wind power is expected to reach 2000GW by 2030. By 2050, wind energy accounted for 25% to 30% of global electricity generation [2]. Offshore wind farm has become a hot spot in the development of new energy sources, because of its abundant wind energy resources, good stability, low turbulence intensity, small wind cutting edge, less occupation of land resources, and small noise pollution [3].

Compared with the construction on the land, offshore wind farm construction has the characteristics of large investment, difficult construction and high risk. Offshore wind turbine foundation accounts for 20% ~ 30% of the total cost of wind farm, according to the proportion of investment in offshore wind farm which has been established at home and abroad [4]. The offshore wind turbine foundation mainly includes gravity based, monopile, pile group cap foundation, suction bucket, and floating type. The construction technology of different foundation forms has great differences [5-8]. The high-rise pile cap foundation is widely used in the construction of offshore wind power, accounting for 7 per cent of the 6496 offshore wind turbine foundations worldwide [9]. The design method of high-rise pile cap foundation mainly refers to the design method of cross-sea bridge and oceanographic engineering [10-12]. The construction technology of bridge pile foundation can be used for the construction of high-rise pile cap foundation [13]. Large-diameter monopile foundation is a common choice for most

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offshore wind farms in Europe, while conversely, Asian market is dominated by other fixed-grounded foundation concepts, especially of type high-rise pile cap [14]. According to the characteristics of different seas, different construction technologies of pile cap foundation are needed. The Donghai Bridge offshore wind farm is Asia's first large-scale offshore wind farm to use a high-rise cap pile group foundation successfully [15]. Its geological conditions are silt formation and sand strata. In the Taiwan Strait, the basement of the individual rock in the field is relatively shallow, new construction techniques are needed. The rock-socketed foundation is a new form of high-rise pile cap foundation, which is the first time using in the bedrock seabed in China and Asia. Based on an example of wind farm construction in Taiwan Strait, this paper analyzes and discusses the scheme, construction technology and construction efficiency of high-rise pile cap foundation.

2. Project overview

2.1. Wind energy resources and marine hydrological conditions

The project is located in the middle of the Taiwan Strait. Due to the great influence of "narrow-tube effect" in the Taiwan Strait, this region has a large annual average wind speed, stable wind direction and very rich wind resources. Annual north-north-east is prevailing wind direction, the annual average wind speed is 7.2 m/s, and the annual average number of days without wind only accounts for 5%. The tide of the sea area belongs to the regular semidiurnal tide and the tidal range is about 8 m. The region is a typhoon-prone area and affected by typhoons each year from July to October.

2.2. Engineering geology characteristics

The geological conditions of the area are complex: the upper layer is Quaternary marine deposit and the lower layer is Yanshan period granite. The Quaternary marine deposit from top to bottom respectively is shown in table 1.

Table 1. The Quaternary marine deposit.

Number	Stratigraphic subdivision	Layer thickness (m)	Standard Penetration Test (SPT)
1	silt	0.6 ~ 1.9	
2	fine sand, medium-dense to dense	7.8 ~ 8.25	17 ~ 32
3	medium coarse sand, slightly dense to medium-dense	3.15 ~ 7.2	10 ~ 23
4	clay	4.6 ~ 11.9	
5	medium coarse sand, slightly wet	1 ~ 3	20 ~ 23

The layers of Yanshan period granite from top to bottom respectively are shown in table 2.

Table 2. The layers of Yanshan period granite.

Number	Stratigraphic subdivision	Layer thickness (m)	Drillability level
1	completely weathered granite, rock structure is basically destroyed, feldspar and other minerals are seriously weathered	3.2 ~ 5.1	2
2	granular highly weathered granite, most of the rock structure is destroyed	3.4 ~ 9.2	5
3	cataclastic semi-weathered granite, jointed fracture development	0.35 ~ 4.8	6

4	weak-weathered granite	top elevation -23.64 ~ -44.93 m	7 ~ 9

2.3. Construction characteristics

Analyses of the wind energy, marine hydrological conditions and engineering geology conditions in the sea area, the main construction characteristics of the project are as follows:

- The sea is rough, the number of effective operation days is relatively small. The area is a typhoon prone area, and the construction equipment and construction technology requirements are high.
- There are a number of islands and reefs in the field, the seabed topography fluctuation is large, the stratigraphic distribution is uneven and the sediment thickness varies greatly. Different construction techniques should be chosen according to different sea conditions. The basement of the individual rock in the field is relatively shallow and the depth of the pile foundation cannot meet the design requirements, so the rock-socketed construction is necessary. The pile foundation diameter is large, all of them are inclined piles, the rock drillability level is high, and so the construction is very difficult.
- The moulding of the cap is a one-time large volume of concrete pouring. Concrete pouring and maintenance are more difficult at sea.
- The situation is complicated. There are obstructions such as water pipes, submarine cables and sunken ships in the field, which should be probed, avoided and cleaned before construction.

3. High pile cap foundation design

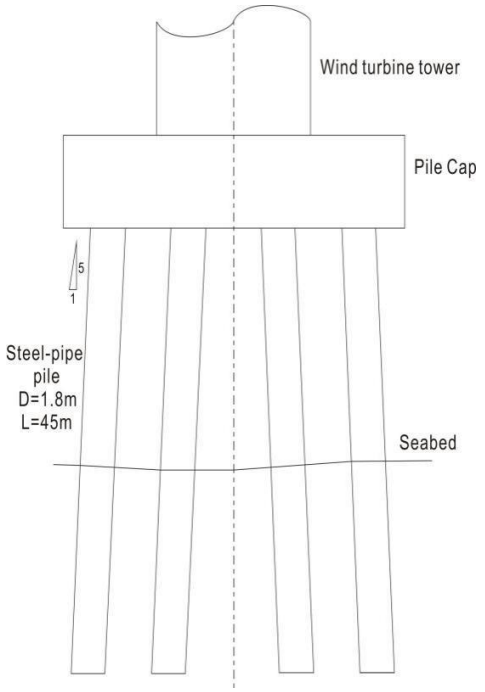


Figure 1. Schematic diagram of friction piles foundation.

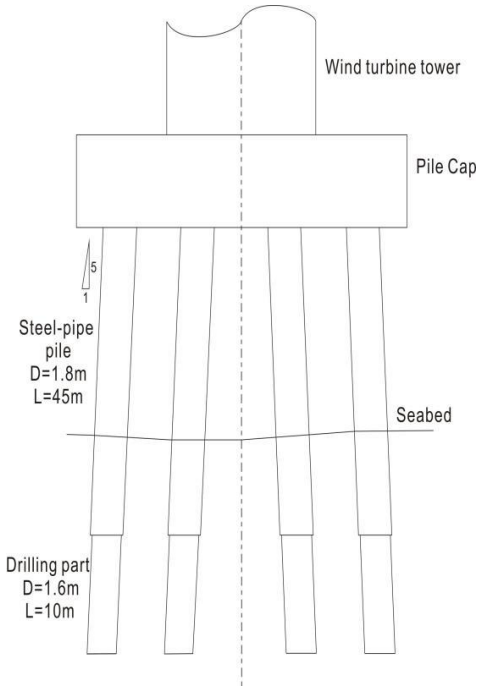


Figure 2. Schematic diagram of rock-socketed piles foundation.

The high pile cap foundation mainly consists of pile and cap. The pile foundation mainly carries axial load, horizontal load and bending moment. The platform combines the wind turbine tower with the pile foundation, which plays the role of load transfer and bearing. The pile foundation forms of high pile cap include friction piles and rock-socketed piles. The foundation of the project adopts the high pile cap and

the pile foundation has both friction piles and rock-socketed piles. Eight steel pipe piles with a diameter of 1.8 m (wall thickness 28 ~ 30 mm) are used as foundation piles. Eight foundation piles are arranged evenly along the circumference of 10 meters in diameter on the bottom of the base and their slope is 5:1. Granular highly weathered or cataclastic weathered granite is designed to be the bearing layer of the friction piles, as shown in figure 1. Weak-weathered granite is designed to be the bearing layer of the rock-socketed piles. The rock-socketed part is 10 m in length, 1.6 m in diameter and adopts C40 reinforced concrete structure, as shown in figure 2.

4. Construction technologies

According to the design requirements and construction characteristics of the high pile cap, the construction technologies used in this project include the production and transportation of steel pipe piles, pile foundation construction, and pile cap construction.

4.1. Production and transportation of steel pipe piles

Steel pipe pile is delegated to the professional steel processing enterprises for production and transported to the construction site. The production processes of steel pipe pile include steel pipe pile section, welding and corrosion. The steel pipe piles are transported by 3000 t square barge, which is equipped with anchor system.

4.2. Pile foundation construction

4.2.1. The construction technologies of the friction pile foundation. The construction technologies of the friction pile foundation are shown in figure 3.

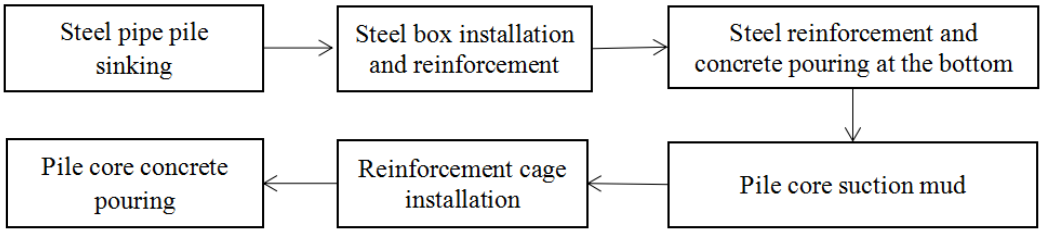


Figure 3. The construction technologies of the friction pile foundation flow diagram.

The S800 hydraulic hammer and piling guide rack are used to carry out pile-sinking operations. The hydraulic hammer is fixed to the piling rack, which can effectively avoid the influence of the eccentric force on the sinking pile and ensure the inclination of the pile body. This process can be used to sink the steel pipe piles directly to the design elevation. The construction process of sinking piles is shown in figure 4.

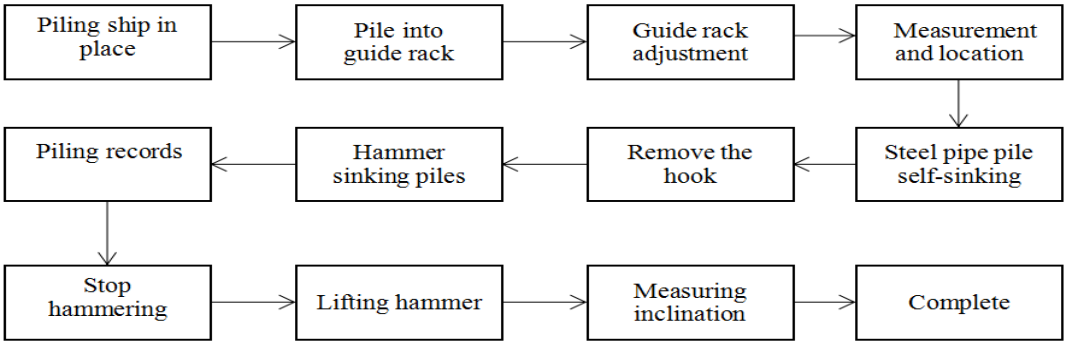


Figure 4. Sinking pile construction process flow diagram.

Friction pile core construction does not need to set up special construction platform. After the completion of the pile sinking, steel boxed cofferdam is directly installed into the top of the steel pipe pile, then reinforcement and concrete pouring are carried out. The bottom concrete structure is the platform for the construction of subsequent pile cores. In order to improve the overall rigidity of the foundation, increase uplift resistance of single pile foundation, mud suction operation and C40 micro-expansion concrete pouring are carried out inside piles.

4.2.2. The construction technologies of the rock-socketed pile foundation. The construction technologies of rock-socketed pile foundation are shown in figure 5.

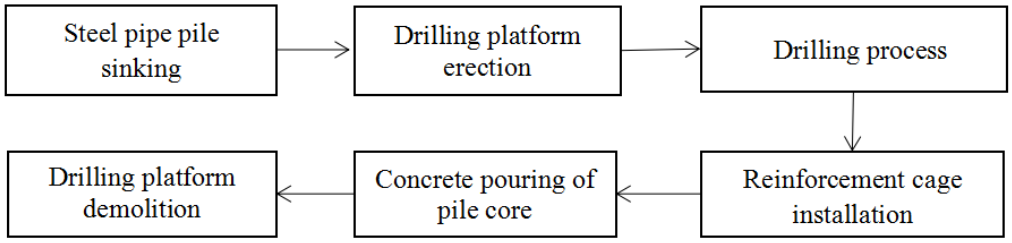


Figure 5. The construction technologies of rock-socketed pile foundation flow diagram.

Friction piles and rock-socketed piles have the same construction technologies of sinking piles. In the position of rock-socketed wind turbine, the installation of integral drilling platform is required when steel pipe piles are sunk. The drilling platform is anchored on the steel pile through the hydraulic system. Use ZJD-3000 drilling rig to carry out drilling construction by gas-lift reverse circulation drilling technology, drill to design depth and then carry out pile core concrete pouring and drilling platform demolition.

The traditional drilling platform erection is built at sea. Due to poor working conditions, small working area, the efficiency is very low. In this project the drilling platform is built on land and then the whole drilling platform is lifted to the top of steel pipe piles, so the construction efficiency improves a lot.

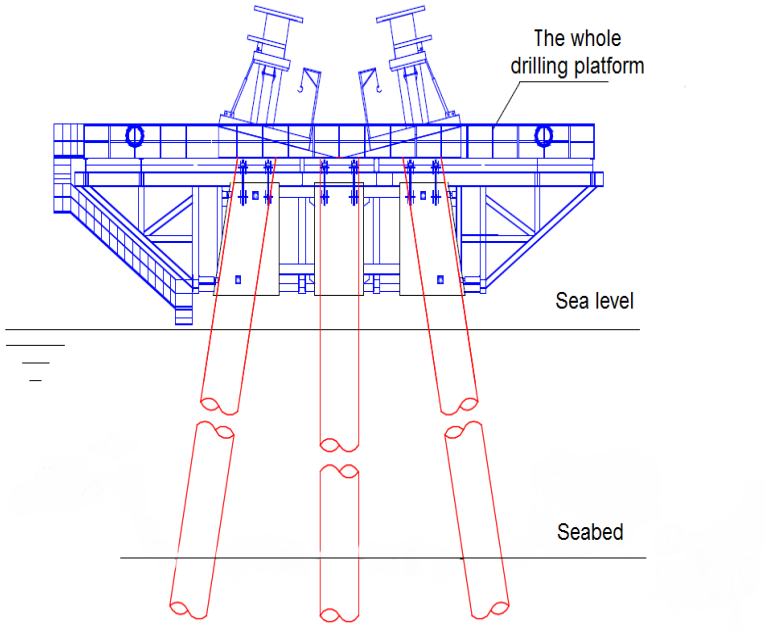


Figure 6. Schematic diagram of the whole drilling platform.

The main support structure of the assembled drilling platform is the steel frame. The drilling platform is 24 m in length and 19.2 m in width. The roof is the lattice type structure, which directly bears the drilling rig weight. The slope of the steel structure at the bottom of the drilling platform is the same as that of the steel pipe pile. The platform and steel pipe piles are anchored by hydraulic system, as shown in figure 6.

Drilling processes mainly include drilling rig in place and installation, drilling, hole cleaning, reinforcement cage hanging and concrete pouring.

- Drilling rig in place and installation. When the drilling platform is installed, the rig is hoisted to the position by crane ship. To ensure that the center of the drill pipe and the steel pipe pile are in a straight line, adjust the slope of the drilling rig and fix the drilling rig on the platform. Deviation is no more than 2 cm.
- Drilling. In the drilling process, the air-lift reverse circulation drilling technology is adopted with the cone bit and φ 320 mm drilling pipe. In order to ensure the inclination of the drilling hole, the centralizer is arranged on the drill pipe near the drilling bit. The compressed air is sent to the bottom of the hole through the air supply pipe, which is arranged on the drill pipe, and the high pressure air and water are mixed at the bottom of the drilling pipe, forming a low density inflatable drilling fluid. The negative pressure is formed in the drilling pipe. Under the pressure difference, the drilling fluid carries the rock debris at the bottom of the hole to the ground. High speed and low pressure drilling process are used when drilling in clay layer. When drilling in sand and pebble, the drilling pressure increases slightly and the air volume increases. When drilling in rock formation, the large drilling press and low speed are used. Drill into the design depth and drilling hole completion.
- Hole cleaning. The air-lift reverse circulation process is used to clear the hole. The compressor sends compressed air through a pipe to the bottom of the hole. Rock debris on the bottom of the hole is suspended by the low density mixed liquid. Circular clearance between drill pipe and steel pipe pile is filled with clear water to drain out the rock debris. The thickness of sediment at the bottom of the hole should be less than 3cm after cleaning. If the sediment is larger than the design requirement, secondary hole cleaning shall be carried out.
- Steel reinforcement cage hanging. The steel reinforcement cage is made and completed on the pier, and then it will be transported to the construction site by transport ship. When placed, it should sink slowly and reduce the friction with the steel pipe. In order to guarantee the vertical degree of the reinforcement cage and the thickness of the concrete protection layer of the outside of the steel cage, after placed in the pile hole, the cage should be fixed.
- Concrete pouring. Before pouring concrete, check hole depth and sediment thickness. To ensure the quality of the concrete reinforcement, the concrete pouring must be done at one time continuously. The internal diameter of the catheter is 250 mm and the spacing between the tubes is 3 meters. The height between the bottom of the tube and the bottom of the hole (the design specification is 300 ~ 400 mm) and the verticality must be ensured to meet the design requirements. The concrete is provided by the concrete mixing ship at the scene. Calculate the amount of concrete in the first pot and then place enough concrete in the funnel. At the beginning of pouring, quickly open the valve. Under concrete's own gravity, the water within the catheter and circular clearance is squeezed out so that the concrete quickly seals bottom and the buried pipes are more than 1m. During the process of continuous concrete pouring, the catheter is slowly lifted with a range of about 15 ~ 60 cm each time. Concrete pouring must be done within initial setting time of concrete. Pouring speed should be moderate, too slow will lead to the formation of hard shell on surface of concrete, too fast will lead to collapse of the hole [16].

4.3. Pile cap construction

The processes of the pile cap construction mainly include manufacture and installation of steel boxed cofferdam, bottom concrete pouring, installation of foundation ring, cap assembling reinforcement, cap

concrete pouring, concrete curing and formwork removal of steel boxed cofferdam. The pouring of cap structure is carried out at the sea. The pile cap structure is a cylindrical structure with a diameter of 14 m and a height of 5.6 m. The bottom concrete (a height of 0.8 m) and the cap concrete (a height of 4.8 m) are both poured at once. Pouring concrete pile cap belongs to large volume concrete pouring, which must be constructed strictly according to the design requirements and the code for construction of mass concrete. The water cooling system is used for the curing of concrete in the inner and top of the cap, and the curing days are not less than 14 days. The internal temperature of concrete cap is monitored by the large temperature monitoring system.

Compared with the completed Donghai Bridge Wind power project, the main feature of the project is the need for construction of rock-socketed. At the beginning of the project, the traditional construction technology similar to the Donghai Bridge Wind power project was adopted, but the efficiency was low. The construction period of the friction and rock-socketed pile foundation were 39 days and 122 days respectively. Therefore, it is necessary to optimize the construction technology of high-pile cap foundation. Compared with the traditional construction technology, the construction technologies used in this project have the advantages of low cost, simple operation, high efficiency, and high security. In this project the technical optimizations are as follows: 1) the piling hammer is fixed on the guide rack to improve the efficiency of sinking piles; 2) the drilling platform adopts an integral platform which is assembled as a whole; 3) the steel boxed cofferdam is assembled at the wharf which is holistically lifted and dismantled. Most of the steel bars and embedded parts are arranged in the shore in advance and the rest is completed at sea. After the optimization of the construction technology the construction efficiency is greatly improved. The construction period of the friction pile foundation is shortened by 10 days, and the construction period of the rock-socketed pile foundation is shortened by 48 days.

5. Environmental impact of foundation construction

Wind power construction will have an impact on the environment. The specific impact is as follows:

- The sea is occupied and destroyed. Engineering construction will cause local sea water pollution.
- Marine life. Destroys the habitats of marine life, damages and disturbs marine life.
- Bird. Risks to birds from offshore wind construction arise from four main potential impacts: direct loss of habitat; displacement; collision risk; avoidance behaviour / barrier effect [17].
- Traditional fisheries.
- Impact of maritime traffic.

The new high-rise pile foundation construction time is short, the impact is a local change in species composition. During the construction period, corresponding measures should be taken to reduce the impact on the environment.

- The monitoring and management of environmental quality should be strengthened.
- Adopt ecological remediation measures. Increase the restocking of fish and shrimp.

6. Conclusion

Offshore wind power is the future trend of wind power industry. China's offshore wind power is in a rapid development stage. The foundation of high pile cap is widely used in offshore wind farm construction. In this study, the construction technology of friction and rock-socketed high-rise pile cap foundation are introduced in detail, and technological process of the pile foundation and pile cap construction are emphasized. Practice has proved that construction technique of pile hammer, integral drilling platform and integral steel boxed cofferdam can meet the design requirements in Taiwan Strait. After process optimization, the efficiency of friction piles foundation and rock-socketed piles foundation are shortened by 10 days and 48 days respectively. The high-rise pile cap foundation construction technology is safe, reliable and economical and it will provides some reference value for the construction of offshore wind farm in China.

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