

Study on Horizontal Loading of Large Diameter Single Pile of Offshore Fan on Soft Clay Seabed Foundation

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Abstract: Vigorously developing offshore wind power is an important measure to achieve China's "dual carbon" goal. For offshore wind turbines, the foundation embedded in the seabed is directly related to the safety and stability of the wind turbine, and is the most important part of wind power design. At present, in the offshore wind power construction within 40 m, large diameter single pile foundation is the most widely used foundation form. For the design of single pile foundation, it is necessary to ensure that the ultimate load of foundation can withstand the most extreme external load. Secondly, it is necessary to ensure that during the 25-year service period of the fan, the cumulative deformation of a single pile at the mud surface under the cyclic load of wind and waves does not exceed the value specified in the code; Finally, it is necessary to ensure that the wind power structure does not occur fatigue damage under the action of reciprocating dynamic load. Such strict design criteria, coupled with the soft clay seabed with poor mechanical properties widely distributed in the sea area of China's wind farms, bring severe challenges to the design of single piles.

Keywords: Soft clay, Offshore fan, Large diameter single pile, Pile-soil interaction.

1. Introduction

Energy is the cornerstone of the survival and development of human society and the core driving force for world economic growth. Throughout history, every productivity change in human society has been closely linked to energy. Since the second Industrial Revolution, the consumption of non-renewable energy, mainly coal and oil, has been growing rapidly, making fossil fuels exhausted and the global energy crisis intensified. At the same time, the huge amount of carbon dioxide emitted by the burning of fossil energy makes the earth's temperature continue to rise (as shown in Figure 1), which in turn causes the serious climate crisis of global warming. Under the double crisis of energy and climate, countries around the world have accelerated the exploration and development of new energy sources such as wind energy, solar energy and hydrogen energy, and low-carbon sustainable development has become a worldwide theme. As the developing country with the largest economy and the largest carbon emission in the world, China faces greater pressure on energy conservation, emission reduction and low-carbon economy. In order to achieve this goal, the 2021 government Work report clearly points out that it is necessary to optimize the industrial and energy structure and vigorously develop new energy. Vigorously developing offshore wind power is an important measure to achieve China's "dual carbon" goal. For offshore wind turbines, the foundation embedded in the seabed is directly related to the safety and stability of the wind turbine, and is the most important part of wind power design. At present, in the offshore wind power construction within 40 m, large diameter single pile foundation is the most widely used foundation form. For the design of single pile foundation, it is necessary to ensure that the ultimate load of foundation can withstand the most extreme external load. Secondly, it is necessary to ensure that during the 25-year service period of the fan, the cumulative deformation of a single pile at the mud surface under the cyclic load of wind and waves does not exceed the value

specified in the code; Finally, it is necessary to ensure that the wind power structure does not occur fatigue damage under the action of reciprocating dynamic load. Such strict design criteria, coupled with the soft clay seabed with poor mechanical properties widely distributed in the sea area of wind farms in China, bring severe challenges to the design of single pile.

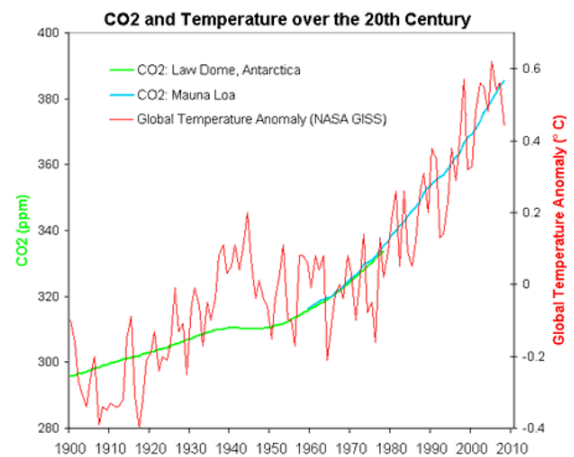


Figure 1. Evolution of global temperature and atmospheric CO2 concentration

2. Development Status of Offshore Wind Power

Among many new energy industries, offshore wind power is favored by China and other countries around the world because of its large reserves, no arable land and low environmental noise pollution. Denmark was the first country to build the world's first offshore wind farm, Vindeby Wind Farm, in 1991 (see Figure 2). The wind farm is located at an average offshore distance of 2 km, the maximum water depth of 4 m, the total installed capacity of 5 MW, by 11 0.45 MW wind turbines, the annual power generation can meet the

annual electricity demand of 2200 households.



Figure 2. The world's first offshore wind farm - Vindeby Wind Farm in Denmark



Figure 3. Global offshore wind power installed capacity trends

China, as a country with a coastline of 1.8 kilometers and more than 3 million square kilometers of usable sea area, has unique advantages in the development of offshore wind power. China's offshore wind energy resources are mainly concentrated in the southeast coastal waters, the average density of wind energy exceeds 300 watts/square meters, and the Taiwan Strait is the most abundant area of offshore wind energy resources in China. Such excellent wind energy resource conditions bring convenience to the large-scale development of offshore wind power. The results of the wind energy resources survey show that in the offshore areas with water depths less than 50 m, China's offshore wind energy can be developed up to 500 GW, which is equivalent to the installed capacity of 20 of the world's largest hydropower station - the Three Gorges hydropower Station (China Wind Power Development Roadmap 2050) Compared with European countries, China's offshore wind power development started late. In 2010, the 19th year after the completion of the world's first offshore wind farm, the Shanghai Donghai Bridge wind Farm with a total investment of about 2.4 billion yuan was officially connected to the grid for power generation, announcing the birth of China's first offshore wind farm in a strict sense. The Donghai Bridge Wind Farm has a total installed capacity of 102 MW, consisting of 34 3 MW wind turbines, and an annual generating capacity of 267 million KWH, which can meet the annual electricity demand of about 150,000 Shanghai households. The grid-connected Donghai Bridge offshore wind Farm officially opened the prelude to China's large-scale development of offshore wind power. Although China's offshore wind industry started late, but rapid development. Today, 11 years later, offshore wind farms can be found all over China's 18,000 kilometers of coastline.

By the end of 2020, China's total installed capacity of

Since then, the construction of offshore wind farms has set off a boom around the world, and the installed capacity of offshore wind power is advancing all the way. Figure 1-3 shows global offshore wind capacity trends over the past decade. It can be seen that in just a decade, the global installed capacity of offshore wind power has increased from 3.3GW in 2011 to 32.5GW in 2020, an increase of nearly ten times. In addition, according to the forecast of the National Renewable Energy Laboratory of the United States, the future development of offshore wind power will continue to maintain a strong momentum, the global installed capacity of wind power in 2030 can reach about 200GW, by 2050 is expected to exceed 500GW.

offshore wind power has reached 7.1 GW, accounting for 22% of the global total installed capacity of offshore wind power (32.5GW), second only to the United Kingdom and Germany, ranking third in the world. In 2020, the world's new offshore wind power installed capacity of 5.2GW, of which China has 2.1GW, accounting for 40% of the global new capacity, ranking first in the world. According to the forecast of the Global Wind Energy Council (GWEC), in the next decade, China's offshore wind power will enter a comprehensive and rapid development stage, and by 2030, China's total installed capacity of offshore wind power will reach 58.8 GW, surpassing the UK's 40.3 GW, becoming the world's largest cumulative installed capacity of offshore wind power.

3. Offshore Fan Foundation Form

Offshore wind turbines will be subjected to huge horizontal loads and horizontal overturning moments. These loads are eventually transmitted to the fan base, which is located in the seabed foundation. Therefore, the horizontal bearing performance of the offshore fan foundation is directly related to the stability and safety of the fan unit and is the most critical part in the design of the fan foundation structure [1],[2]. According to the different water depth and seabed soil conditions of the wind power site, the main types of offshore fan foundation are: (1) gravity foundation: the foundation relies on its own gravity to provide stiffness to resist external horizontal and overturning loads; (2) Large diameter single pile foundation: the large diameter hollow steel pipe pile with a diameter of 4-10 m is inserted into a depth of 30-60 m below the seabed, and the load resistance is provided by the soil resistance around the pile; (3) High pile cap foundation: usually consists of 6 or 8 base piles and caps with a diameter of about 2 m, and the depth of each foundation pile is 30-50 m; (4) Barrel foundation: divided into two forms of single

barrel and group barrel, the lower end of the opening and the upper end of the closed, shaped like an upside down round barrel, the barrel diameter can reach 8-20 m, the depth of the soil and the ratio of the barrel diameter between 0.5-1, the use of negative pressure sinking principle into the seabed; (5) Jacket base: the main body is a truss structure, the upper part is connected with the fan tower barrel, the lower part is connected with 3 or 4 piles with a diameter of about 2 m, and the foundation piles are buried 30-50 m to provide resistance; (6) Floating foundation: the fan is fixed on the floating platform, the platform is connected with the lower anchoring system, and the stability of the floating platform and the fan

is ensured by anchoring foundation. At present, most offshore wind farms in China and Europe are located in offshore waters with water depths of less than 40 m. In this water depth range, large diameter single pile foundation, because of its simple structure, convenient installation, construction technology and equipment mature and stand out in the above various foundation forms, become the first choice of offshore fan foundation. At present, the single pile foundation of offshore fan is usually hollow steel pipe pile with diameter $D=4-10$ m, the ratio of pile depth to pile diameter L/D is mostly within the range of 3-10, and the wall thickness is 6-10 cm[3], [4].



Figure 4. Typical large diameter single pile foundation of offshore fan

4. Design Criteria for Offshore Wind Turbine Foundations

The design of offshore wind turbine foundation usually meets the following criteria (DNVGL, 2016) : (1) Limit state design criteria (ULS) : Firstly, the ultimate environmental load borne by the wind turbine is calculated according to the wind condition and ocean hydrological conditions of the wind farm site; Then the size of the foundation is designed to ensure that its maximum bearing capacity exceeds the most extreme external environmental load, so as to prevent the soil around the foundation from being completely destroyed and the fan from overturning when it is subjected to the most extreme environmental load. Limit state design is the foundation of fan foundation design. (2) Normal use state design criteria (SLS) : The external wind, wave and flow load of the offshore fan is not a constant static force, but a long-term cyclic power. During the service period of the fan, the number of cyclic loads on the fan foundation can reach 107-108 times [5],[6]. Under the action of cyclic loads, the stiffness of the soil around the foundation continues to weaken, and the plastic strain continues to accumulate, which eventually leads to the continuous accumulation of the foundation displacement [7],[8]. According to the requirements, in order to ensure the normal and effective power generation of the offshore fan during its service period, the design criteria for the normal operation of the fan foundation shall ensure that the allowable cumulative deformation of the fan during the entire service period shall be less than 0.25° [9]. (3) Fatigue design criteria (FLS) : offshore fan infrastructure is mostly steel components, under the cyclic load of wind, wave and flow, its fatigue behavior is one of the control factors for fan foundation design. Fatigue failure is also one of the major potential failure modes of offshore wind turbine infrastructure. Fatigue design criteria require that the fatigue life of the fan

foundation should be longer than the service life of the fan under the combined action of various environmental loads. (4) Target frequency design criteria (TFLS) : Offshore wind turbines are tall flexible structures, and their dynamic effects are sensitive. In order to prevent resonance, the target frequency design criteria require to ensure that the natural vibration frequency of the fan under the foundation stiffness does not coincide with the frequency of wind, wave and flow, and at the same time avoid the frequency of fan blade rotation (1P frequency) and the shielding effect frequency (3P frequency) caused by the blade sweeping the tower barrel position. Currently, offshore wind turbine designs are usually designed so that the natural vibration frequency of the wind turbine is between 1P and 3P frequencies. In order to consider safety redundancy, the DNVGL specification further requires that the fan natural vibration frequency should be within the range of 1P and 3P frequency offset $\pm 10\%$.

5. Conclusion

To sum up, this paper introduces in detail the current research status of large diameter single pile horizontal load of offshore fan on soft clay seabed foundation at home and abroad, summarizes and reviews the existing design forms of offshore fan foundation, and introduces in detail the existing design criteria of offshore fan foundation applied to engineering.

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