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Summary of Research on the Horizontal Bearing Behavior of Wing-monopiles

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Abstract

Wing-monopiles have received extensive attention in recent years due to their superior engineering properties. Researchers have studied the horizontal bearing capacity of wing-monopiles through indoor tests, numerical simulations and theoretical analysis. From the aspects of the horizontal bearing characteristics of wing-monopiles and the influencing factors of bearing capacity, the research and development of the horizontal bearing characteristics of wing-monopiles at home and abroad are reviewed, and the current research progress in the calculation of the bearing capacity of wing-monopiles is summarized.

Keywords

Wing-monopile; Wing Plate; Lateral Load; Bearing Capacity.

1. Introduction

The 21st century is an important century for the development of ocean engineering. With the rapid development of offshore cities and the massive construction of ocean engineering, their development has become the mainstay of my country's urban economic development. The development of marine economy will inevitably rely on the construction of marine engineering facilities, such as the construction of large offshore projects such as cross-sea bridges, transmission line towers, offshore drilling platforms, ports and docks, and wind turbines. Taking the wind turbine pile foundation as an example, according to statistics from the Global Wind Energy Council (GWEC), the global offshore wind power installed capacity increased by 6.1×10^6kW in 2019, and the cumulative installed capacity reached 2.914×10^7kW, an increase of 35.5% over 2018. From 2015 to 2019, the global offshore wind power market grew at an average annual rate of nearly 16%. China has become the country with the most new installed capacity for two consecutive years. In 2019, my country's newly installed offshore wind power capacity was 1.98×10^6kW, and the cumulative installed capacity was 6.42×10^6kW. The planned goal of 5×10^6kW for the final installed capacity of the 13th Five-Year Plan was completed one year ahead of schedule, ranking third in the world after Britain and Germany. According to the plans of various provinces, Jiangsu, Guangdong, etc. are key areas for the development of offshore wind power in the future, and my country's offshore wind power will also enter a period of rapid development [1].

Due to its special location and use, offshore wind turbine pile foundations must not only be affected by their own gravity, but also have to resist the effects of long-term horizontal dynamic loads such as wind load, wave impact, impact of ships and floating objects on the sea, etc. This results in permanent lateral deformation of the pile foundation, and once the rotation angle of the pile foundation exceeds 0.25°, the wind power foundation will not be able to serve as scheduled. In order to meet this requirement in the project, it had to be realized by increasing the buried depth of the single pile, which

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directly led to a substantial increase in basic investment. According to statistical data, the cost of offshore wind turbine pile foundations accounts for 10%-15% of the total cost of land wind turbine foundations.

In order to improve the adaptability of pile foundations to different engineering characteristics, different foundation conditions, and to reduce the requirements of engineering costs, special-shaped piles or variable-section piles have become a new trend in the development of pile foundation engineering. Some special-shaped piles have received extensive attention and application in the engineering community. Classified according to the purpose of alienation, special-shaped piles can be divided into two categories: vertical reinforcement and horizontal reinforcement. Because the horizontal load-bearing properties of piles are generally determined by the interaction of shallow piles and soil, the dissimilation of horizontal reinforced special-shaped piles is mostly achieved by increasing the projected area of the shallow pile-soil interface in the vertical plane, such as wing-monopiles, shallow enlarged head piles, etc. Therefore, the study of the bearing behavior of wing-monopiles under horizontal loads can improve the safety and economy of large-scale engineering projects, and has a guiding role in the design and construction of pile foundations.

2. Introduction of Wing-monopile

Wing-monopile is a new type of structure for offshore wind turbine single-pile foundation. A wing plate is set on the pile body under the mud surface to increase the soil resistance in front of the pile, thereby reducing the horizontal displacement and improving the horizontal bearing capacity of the foundation. From another perspective, wing-monopiles can reduce the pile diameter on the basis of ensuring the horizontal bearing capacity of the pile foundation, thereby reducing construction difficulty and saving costs, and further promoting the development of marine engineering.

Fig. 1 shows a schematic diagram of a wing-monopile and two alternative configurations. Steel piles with protrusions can be realized by welding "wing plates". On precast concrete piles, the bulge can be created by integrating steel plates into the reinforcement or by steel rings applied later. Since the loading direction may change with external conditions such as wind or tide, a structure with three or four wings may best meet the requirements. The steel plate on the ground can improve the stability of the pile foundation and prevent erosion.

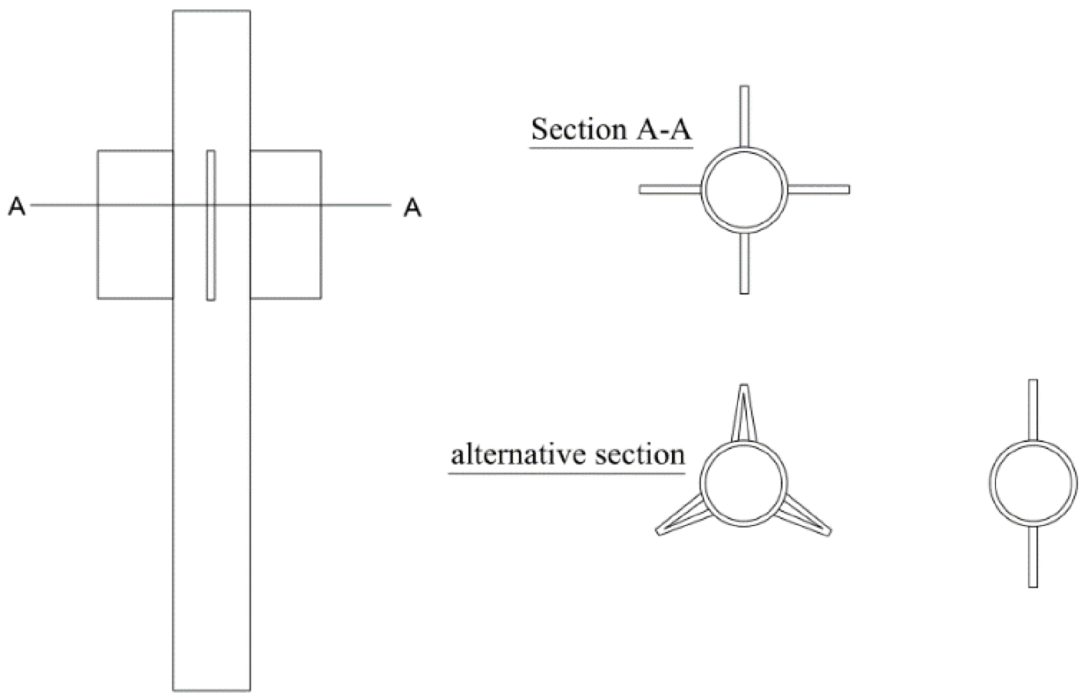

Fig. 1 Schematic diagram of wing-monopile

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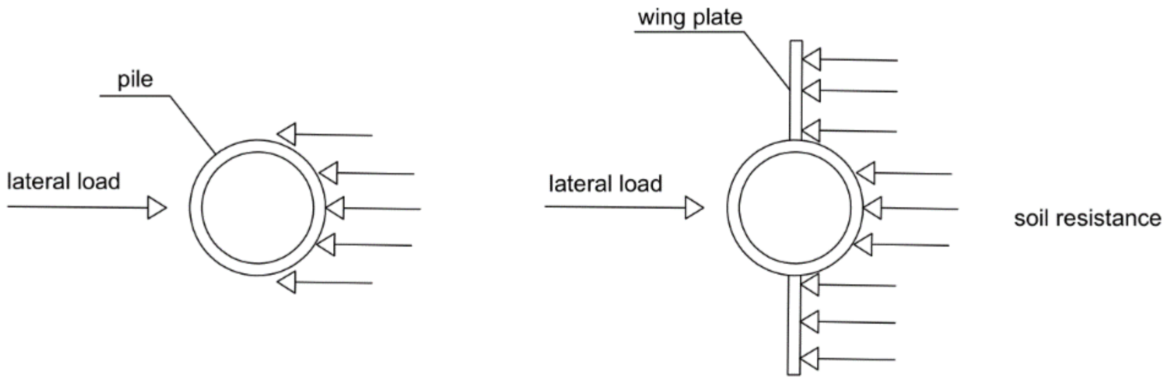

Fig. 2 Working mechanism of wing-monopile

3. Research Progress in Recent Years

Broms [2] proposed the idea of increasing the horizontal bearing capacity of the foundation pile by setting a wing plate on the side of the pile to obtain a larger soil reaction force. Subsequently, many scholars conducted related experiments and simulations for this idea in 1972. Regarding the test method, whether it is an indoor model test or an in-situ test, it has its advantages and disadvantages. The indoor model test can be free from the limitation of the test site, and the test parameters can be changed as needed to obtain more ideal research results. However, the indoor model test cannot fully simulate the characteristics of the pile foundation, which makes the research results have certain limitations; although the on-site in-situ test can fully reflect the characteristics of the pile foundation and obtain the research results consistent with the actual project, the workload is large and suffers, the space is limited and it is not economical. Wing-monopiles are a new type of foundation. The theoretical system under horizontal load is still immature. The horizontal load test of large-diameter wing-monopiles is difficult and costly, and the accuracy of the measured pile side soil resistance is difficult to meet the theoretical analysis requirements. There is no experimental data in this regard. The main research progress focuses on indoor large-scale model tests and finite element software numerical simulation.

3.1 Research Progress of Indoor Tests

Wen Songlin [3] conducted an indoor physical test of "symmetrical two-wing plate arrangement" wing-monopiles in sand in 1990. The test results showed that the horizontal bearing capacity of square wing plated wing-monopiles was greater than that of rectangular wing plated wing-monopiles, But the test piles and wing panels are simulated by hard plastics, which has certain limitations.

Jan Dührkop et al. [4] concluded through a model test in 2008 that in a soil with greater rigidity, the rigidity of the wings needs to be increased to obtain better results.

Peng J et al. [5] used numerical calculations and indoor model tests to analyze the working performance of wing piles in sand and believed that the setting of wing plates can effectively reduce the displacement of the pile head and improve the utilization rate of shallow soil resistance.

Li Wei et al. [6] used constant gravity (1g) model tests in 2013 to study the action mechanism of wing-monopiles in sandy silt. The results show that the setting of wing plates can significantly improve the utilization of shallow soil resistance. The increase rate is related to the shape parameters of the wing plate and the buried depth. When the horizontal load of rigid piles without wings and wing-monopiles reache the ultimate bearing capacity, the rotation center of the pile body is about 0.75 times the depth of the pile foundation.

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Li Wei et al. [7] conducted a centrifugal model test in 2015 and found that the size of the wing plate is the main factor affecting the horizontal bearing performance of a wing-monopile. The greater the width or length of the wing, the greater its horizontal bearing capacity. However, due to the influence of manufacturing, transportation, implementation (piling), etc. in practical applications, the rational selection of the connecting part of the wing plate and the pile foundation and the reasonable selection of the wing plate size are the key to the design.

Zou Guihua et al. [8] questioned the conclusion drawn by Wen Songlin [3] in 2016 that the horizontal bearing capacity of square wing-slab winged piles is larger than that of rectangular wing-slab winged piles when the wing area is the same. He thinks this conclusion is only suitable for specific engineering environment. The horizontal load-bearing behavior of the pile is affected by many factors such as the pile side soil and the stiffness of the pile body. It should be selected according to the specific situation of the project. When the stiffness of the pile body is relatively small, it is recommended to use a square wing plate. Rectangular wings can be considered when the rigidity of the body is large.

3.2 Research Progress of Numerical Simulation

Li Wei et al. [9] conducted a comparative analysis of the dynamic characteristics of a wing-monopile in 2012 through modal analysis, harmonic response analysis, transient analysis under impact load, and wave spectrum analysis under wave load.It is proved that wings can reduce the dynamic response of a single pile.

Nasr et al. [10] used finite element numerical calculation in 2014 and found that when the ratio of wing plate length to pile length LF/LP=0.4, the maximum pile displacement and pile rotation angle reduction effect can be obtained, and the best width of the wing plate is the pile diameter D.

Wang Xipeng et al. [11] calculated and analyzed the influence of wing plate area and aspect ratio on the horizontal bearing capacity of foundation piles based on ABAQUS finite element software in 2016. It is concluded that compared with a single pile, the horizontal displacement at the mud surface of the wing-monopile is reduced by about 49%, and the maximum bending moment of the pile body is reduced by about 11%. For a wing-monopile with a pile diameter of 5 m on a soft clay foundation, the horizontal bearing capacity of the wing plate can be fully utilized when the side length of the square wing plate is less than 1.6 D.

Yu Renbin et al. [12] conducted a finite element numerical analysis on the horizontal bearing characteristics of large-diameter wing-monopiles in clay soil foundation in 2016, and obtained the soil deformation pattern around the winged piles. Furthermore, the equivalent enlarged head pile model of offshore wind turbine wing-monopile under horizontal load is proposed.

Chen Canming et al. [13-14] simulated large-diameter steel pipe piles in silty clay based on ABAQUS finite element analysis software in 2018. It is believed that the effect of the elongated wing plate on the horizontal bearing capacity of the wing-monopile is obviously better than that of the vertical elongated wing plate under the same wing area. The effect of inverted trapezoidal wing panels on the horizontal bearing capacity of wing-monopiles is better than that of regular trapezoidal and rectangular wing panels. When the rigidity of the wing plate is significantly greater than the stiffness of the pile body, the ultimate bearing capacity is controlled by the maximum stress at the connection between the wing plate and the foundation pile. The relative stiffness 1.0-2.0 is a reasonable ratio of the stiffness of the wing plate to the pile body.

Hu Yezhi et al. [15] in 2019 believed that the loading direction has an impact on the horizontal bearing capacity of the wing-monopile. When the angle between the horizontal load and the front wing plate increases, the displacement of the pile body increases and the displacement zero point moves downward.

In 2019, Hu Xin et al. [16] analyzed the pile top displacement and the deformation mode of the soil around the pile in expansive soil foundation.

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He Jianxin et al. [17] used ABAQUS finite element calculation software to study the load-bearing behavior of wing-monopiles with symmetrically arranged two-wings, three-wings and four-wings in soft clay foundations in 2020. It is concluded that although the pile body stress is higher than that of a single pile when the inclination rate of the pile body reaches 4‰, it is still far less than the allowable strength of the material, and the force of the wing-monopile is more reasonable than that of a single pile.

4. Research progress of calculation methods

Since the new-type wing-monopile has not been put into engineering practice on a large scale, there is no unified standard for the calculation of the bearing capacity and deformation of the wing-monopile under the horizontal load.

Nasr et al. [10] proposed the efficiency coefficient of the wing plate from the perspective of bearing capacity in 2014, and related the efficiency coefficient of the wing plate to the horizontal ultimate bearing capacity of the wing pile, and gave an empirical expression for the efficiency of the wing plate:

$$H_U(N) = -17.21 + 67.79\left(\frac{L_F}{L_P}\right) + 12.75\left(\frac{W_F}{D_P}\right) + 2.12\left(\frac{L_P}{D_P}\right) \tag{1}$$

$$\text{Wing plate efficiency} = 0.84 + 1.55\left(\frac{L_F}{L_P}\right) + 0.275\left(\frac{W_F}{D_P}\right) \tag{2}$$

Where H_U is the ultimate lateral load, N; D_P is the pile diameter, m; L_P is the embedded length of pile, m; W_F is the wing width, m; L_F is the wing length, m.

Yu Renbin et al. [12] based on the equivalent enlarged head pile model of offshore wind turbine wing-monopiles under horizontal load in 2016, combined with the p-y curve of large diameter single piles considering the pile diameter effect, established a calculation method for the deformation of wing-monopiles of offshore wind turbines under horizontal loads, and the wing efficiency index is proposed from the perspective of reducing displacement:

$$\mathrm{p} = \frac{y}{\frac{1}{K} + \frac{y}{p_u}} \tag{3}$$

$$\mathrm{K} = \alpha \frac{E_s}{1-\mu_s^2}\sqrt{\frac{D}{D_{ref}}}\left(\frac{E_s D^4}{E_p I_p}\right)^{\theta} \tag{4}$$

$$p_u = \eta S_u D\left(\frac{z}{z_{ref}}\right)^{\lambda} \tag{5}$$

$$\delta = \frac{u_m - u_w}{u_m} \tag{6}$$

In the formula, p is the soil reaction force per unit length of the pile, kN·m^{-1}; y is the horizontal displacement of the pile section, m; K is the foundation reaction modulus in the horizontal direction, kN·m^{-2}; p_u is the limit soil reaction force, kN·m^{-1}; μs and Es are the Poisson's ratio and deformation modulus of the soil; D is the pile diameter, m; D_{ref} is the reference value of pile diameter, generally taken as 1 m; E_pI_p is the stiffness of the pile section; α and θ are fitting parameters; Su is the undrained strength of the clay; z is the depth below the mud surface, m; z_{ref} is the reference depth, taken as 1 m; η and λ are fitting parameters;δ is the efficiency of the wing; u_m is the pile head displacement of the traditional single pile, m; u_w is the pile head displacement of the wing-monosingle pile, m.

Chen Canming et al. [18] proposed the empirical formula for the ultimate bearing capacity of large-diameter wing-monopiles based on the bearing capacity of large-diameter single piles in soft clay

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foundations and the calculation formulas for the influence coefficients of the wing plate parameters of the wing-monopiles:

$$H_{u.FP} = \alpha k_1 k_2 k_3 k_4 H_{u.MP} \tag{7}$$

$$k_1 = 0.0052(\frac{S}{D^2})^3 - 0.0992\left(\frac{S}{D^2}\right)^2 + 0.4529\left(\frac{S}{D^2}\right) + 1.077, \frac{S}{D^2} \in [0.09,3.24] \tag{8}$$

$$k_{2,J} = -0.068\ln\left(\frac{L}{W}\right) + 1.0242, \frac{L}{W} \in [0.39,2.56] \tag{9}$$

$$k_{2,T} = 8.4187(\frac{\theta}{\pi})^3 - 10.411(\frac{\theta}{\pi})^2 + 3.4804\left(\frac{\theta}{\pi}\right) + 0.797, \frac{\theta}{\pi} \in [0.15,0.62] \tag{10}$$

$$k_3 = -0.011\left(\frac{EI}{E_0 I_0}\right)^2 + 0.0387\left(\frac{EI}{E_0 I_0}\right) + 0.974, \frac{EI}{E_0 I_0} \in [0.6,4.0] \tag{11}$$

$$k_4 = -1.7317\left(\frac{Z}{D}\right)^4 + 4.1411\left(\frac{Z}{D}\right)^3 - 3.1842\left(\frac{Z}{D}\right)^2 + 0.7094\left(\frac{Z}{D}\right) + 1, \frac{Z}{D} \in [0,0.8] \tag{12}$$

In the formula, $H_{u.FP}$ is the ultimate bearing capacity of the wing-monopile, N; $H_{u.MP}$ is the ultimate bearing capacity of a single pile, N; α is the comprehensive influence coefficient; k_1 is the influence coefficient of the wing plate area; k_2 is the influence coefficient of the wing plate shape, considering the rectangular and trapezoidal shapes, they are $k_{2.J}$ and $k_{2.T}$; k_3 is the influence coefficient of wing plate stiffness; k_4 is the influence coefficient of the buried depth of the wing plate; S/D^2 is the ratio of the area of the wing plate to the square of the pile diameter; L/W is the aspect ratio of the wing plate; θ is the angle between the hypotenuse of the trapezoid and the upper edge, rad; $EI/(E_0I_0)$ is the ratio of the rigidity of the wing plate to the rigidity of the steel pipe pile equal-thick wing plate; Z/D represents the ratio of the buried depth of the wing plate to the pile diameter.

Hu Yezhi et al. [19] discussed the calculation method of the p-y curve of large-diameter wing-monopiles in marine soft clay foundation in 2018:

$$\frac{p}{p_u} = 0.5\left(\frac{y}{y_{50}}\right)^{\frac{1}{1.3}}, \frac{y}{y_{50}} < 2.46 \tag{13}$$

$$\frac{p}{p_u} = 1.0, \frac{y}{y_{50}} > 2.46 \tag{14}$$

In the formula, p is the standard value of horizontal soil resistance acting on the pile at depth z below the ground surface, kPa; p_u is the standard value of the ultimate soil resistance per unit area of the pile side at depth z below the ground surface, kPa; y is the horizontal displacement of the pile at depth z below the ground surface, mm; y_{50} is the horizontal deformation of the corresponding pile when the soil around the pile reaches half of the limit horizontal soil resistance, mm.

Hu Yezhi et al. [15] adopted a numerical approximation method in 2019 to establish an empirical formula for the loading direction influence coefficient k_5 on the basis of Chen Canming et al. [18]:

$$k_5 = 0.046\theta^2 - 0.092\theta + 1 \tag{15}$$

In the formula, θ is the angle between the lateral load and the front wing plate, rad.

He Jianxin et al. [17] fitted the calculation formula of the horizontal ultimate bearing capacity of symmetrically arranged two-wings, three-wings and four-wings piles with the direction of load in 2020:

$\mathrm{Two-wings:}$

$$\mathrm{H(\theta) = 0.01H_0[92.8 + 2.6cos(0.035\theta) + 2.4cos(2 \times 0.035\theta) + 1.6cos(3 \times 0.035\theta)]} \tag{16}$$

$\mathrm{Three-wings:}$

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$$\mathrm{H}(\theta) = 0.01\mathrm{H}_0[100.9 - 3.3\cos(0.052\theta) + 2.2\cos(2 \times 0.052\theta) - 0.3\cos(3 \times 0.052\theta)] \quad (17)$$

Four − wings:

$$\mathrm{H}\ (\theta) = 0.01\mathrm{H}_0[93.3 + 4.1\cos(0.070\theta) + 1.2\cos(2 \times 0.070\theta) + 1.0\cos\ (3 \times 0.070\theta)] \quad (18)$$

In the formula, $H(\theta)$ is the ultimate horizontal bearing capacity of the wing pile when the load direction is θ, N; H_0 is the ultimate horizontal bearing capacity of the wing pile when the load direction is 0°, N.

5. Conclusion

Wing-monopiles are a new type of foundation. The theoretical system under horizontal loads is not yet mature. There is no field test data yet. The main research progress is concentrated on indoor large-scale model tests and finite element software numerical simulations.At this stage, the bearing characteristics and mechanism of wing-monopiles have been preliminary studied, and progress has been made, but there is no unified standard for the calculation method of horizontal bearing capacity and pile deformation.In the future, it is necessary to propose corresponding calculation methods for different soils. It is also possible to start from multiple angles such as the basic differential equations of piles to gradually improve the theoretical system of horizontally loaded wing-monopiles.

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