Review on Bearing Capacity of Offshore Wind Turbine Single Pile and New Pile-barrel Combination Foundation

Dingyu Ni, Mingzhen Lu

College of Civil Engineering and Architecture, Wenzhou Polytechnic, 325000, Wenzhou, China

Abstract

The development of offshore wind power must rely on reliable offshore engineering platforms. Since the offshore environment is unpredictable and the on-site working conditions are very complex and harsh, it requires humans to have a deeper understanding of the marine environmental conditions, and to design methods and construction techniques for offshore engineering buildings. There must be a greater improvement in order to reduce the project cost, shorten the construction period, reduce the follow-up maintenance and have a longer service life under the premise of ensuring safety and reliability. Therefore, based on the existing engineering technology, there is still a great research prospect to propose a more safe, efficient construction and relatively low cost offshore foundation form. This paper discusses the theoretical research and experimental research of the traditional offshore wind turbine pile foundation and the new pile-bucket combined foundation. The results show that the new pile-bucket combined foundation enhances the horizontal bearing capacity of the single-pile foundation and compensates for the suction bucket foundation in shallow soil. The defect that it is difficult to exert the carrying capacity in soft soil areas.

Keywords

Offshore Wind Turbines; Bearing Capacity; Pile-bucket Foundation; Monopiles.

1. Introduction

As countries around the world pay more and more attention to issues such as energy security, ecological environment, and climate change, accelerating the development of wind power has become a general consensus and concerted action of the international community to promote energy-based development and address global climate change. As a highly competitive renewable energy, wind energy has completed the transformation from experimental demonstration to practical application after years of research and development, and has been applied on a large scale. Wind turbines can be divided into onshore wind power and offshore wind power according to the location of the layout. Today, when land resources are becoming more and more precious, the development of wind turbines that do not occupy land resources and generate more power (the power generation of a single wind turbine is about 3 times that of onshore wind power). Offshore wind power will gradually become the mainstream of wind power generation.

As one of the ancient and common foundation forms, the pile foundation has been used for more than 7,000 years since its initial application. As one of the most traditional foundation forms, the pile foundation has the advantages of high bearing capacity, stable work performance, small settlement, and high level of mechanized construction. High-rise buildings, bridges, port engineering and offshore structural engineering have been applied and developed on a large scale [1-3].

At present, most of the offshore or onshore wind turbine foundations use various types of pile foundations, but compared with onshore wind power foundations, the technical requirements and

ISSN: 2414-1895 DOI: 10.6919/ICJE.202206_8(6).0058

economic costs of offshore wind power foundations are significantly higher. Offshore wind turbine foundation engineering projects are usually huge in size (the superstructure above the mud surface can reach 100m), and in addition to bearing the gravity load of the superstructure and itself, it is also necessary to consider cyclic loads such as wind, waves, ocean currents, and earthquakes of various frequencies. These loads finally act on the pile foundation, which poses a huge challenge to the long-term service of offshore wind turbine engineering.

2. Offshore Wind Turbine Pile Foundation form

2.1 Traditional Pile Foundation form for Offshore Wind Turbines

According to the literature [5-7], the investment proportion of each part of a single offshore wind turbine system is shown in Figure 1. It can be seen that the cost of the wind turbine unit accounts for about 48%, but the cost is relatively controllable because it is mainly prefabricated in the factory. And the cost of supporting structure accounts for about 34% of the project cost of a single fan unit, but there are large fluctuations due to different site conditions. Therefore, the design of the pile foundation is one of the key technologies in the construction of offshore wind farms. How to improve the existing offshore wind power pile foundation and choose a safe and economical foundation design form is the key to the efficient development of offshore wind energy in the future.

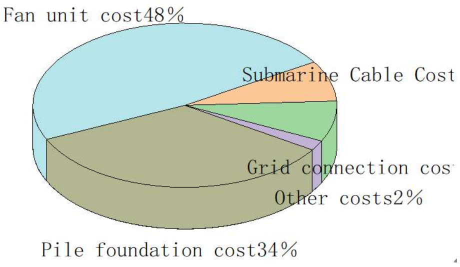

Figure 1. Analysis of the structural cost of offshore wind turbines

At present, the forms of offshore wind turbine foundations can be divided into three categories according to different water depths: foundations in shallow water areas (<30m), foundations in medium water depths (30m~60m), and foundations in deep water areas (>60m). As shown in Figure 2, the shallow water area mainly includes gravity foundation, suction bucket foundation and monopile foundation; medium water depth area has tripod supported by suction bucket foundation, tripod supported by monopile foundation, and jacket supported by suction bucket foundation , Jacket supported by monopile and jacket supported by monopile; there are tension foundation and floating foundation in deep water area. Among them, the monopile foundation is widely used in European offshore wind farms and has become a "semi-standard" method for installing wind turbines in Europe, especially in shallow sea areas with a water depth of 25 meters.

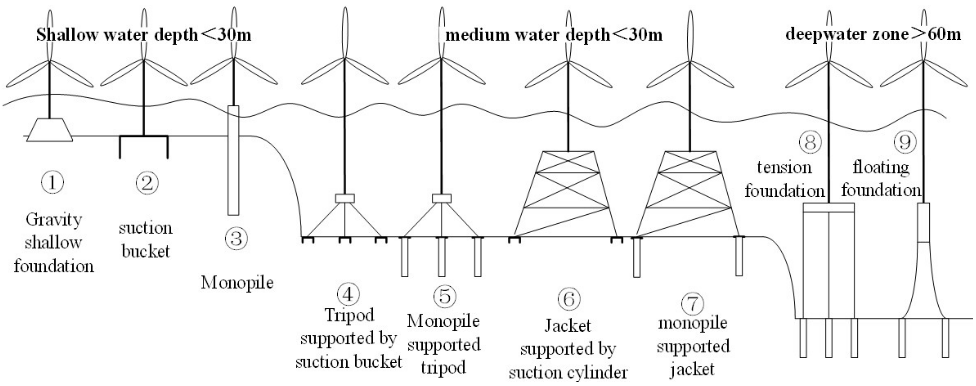

Figure 2. Pile types in different water depths of offshore pile foundations

ISSN: 2414-1895 DOI: 10.6919/ICJE.202206_8(6).0058

The offshore wind turbine foundation (suction bucket foundation, monopile foundation) not only needs to bear the weight of the structure itself, but also needs to support the gravity of the wind power foundation and tower, and at the same time bear the additional wind, waves, ocean currents and other environments that are conducted by the upper structure. load.

① It is a gravity shallow foundation, usually a prefabricated circular cavity structure. The cavity is filled with sand, gravel, concrete and other materials. It mainly relies on its own gravity and the resistance of the soil within the depth range to undertake the level of conduction on the mud surface. load. However, the weight of the offshore gravity foundation is extremely large, usually more than 1500T, which is not conducive to marine transportation and will lead to relatively high construction costs [7]; ② It is a suction bucket foundation, and its shape is usually an inverted buckle with an open bottom and a closed top. The diameter steel drum can be better applied to the sandy soil foundation distributed along the coast of China [8-9]; ③ is a (large diameter) single pile foundation, the main structure has only one prefabricated steel pipe pile, because the structure is simple, the construction The characteristics of high speed and high bearing capacity are widely used in the construction of current offshore wind farms. At present, the single pile foundation accounts for about 50% of the total foundation of offshore wind farms under construction, and 75% of the foundation forms of the completed offshore wind farms are Monopile foundation [10]. The foundations used in medium water depth areas are collectively referred to as multi-legged foundations (④~⑦). This foundation draws on the design method of offshore oil platforms, and consists of multiple single piles or suction buckets connected by jackets to form piles with greater bearing capacity. It is suitable for a wider range of water depths, but the foundation has disadvantages such as high consumption of steel and serious structural fatigue problems caused by too many joint welding. In deep water areas, there are tension and floating foundations that are still in the research stage, which can reduce the problem of stiffness attenuation of pile-soil systems under cyclic loading, which is unique to fixed support structures. Therefore, the large-diameter single pile foundation (pillar diameter 4~8m; pile wall thickness 30~100mm; soil depth 30~70m) is still the most widely used foundation form for offshore wind turbines in shallow seabed areas (20m~30m).

2.2 Optimization of the Construction Period Plan in the Decision-Making Stage of the Project

Offshore wind turbines are huge, and their foundations need to withstand long-term cyclic loads such as wind pressure and wave loads, as well as extreme loads such as storm surges that occur with a certain probability. The complex load conditions put forward strict requirements on the horizontal bearing capacity and deformation characteristics of the wind turbine pile foundation. The design practice shows that the horizontal ultimate bearing capacity of the wind power pile foundation is no longer the dominant design variable, and its horizontal and rotational deformation in the elastic stage is the design point. -2007) [11], the maximum allowable inclination angle of large-scale wind turbine towers with hub heights greater than 100m is only 0.17°[11], which makes it necessary to accurately evaluate the pile foundation deformation characteristics under horizontal loading when designing large-diameter monopile foundations , and seek reasonable foundation and structural reinforcement measures to optimize the horizontal load performance of large-diameter single piles.

Although the single-pile foundation is the most widely used foundation form in offshore wind farms and is suitable for shallow water depths of 20-25m, the single-pile foundation also has its own structural defects, especially in areas with poor seabed soil quality. The maximum inclination angle of the fan is controlled under use. The offshore monopile fan foundation in the soft clay area of the seabed has the construction characteristics of "super long, large diameter and deep penetration", which leads to the bearing advantage and construction convenience of the monopile foundation compared with its construction cost. is no longer obvious. Therefore, it is an urgent engineering problem to seek more reasonable foundation forms and structural reinforcement measures to reduce the diameter and depth of soil penetration of large-diameter single piles in soft soil seabed areas.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202206_8(6).0058

In recent years, due to the advantages of convenient construction of suction bucket foundation, it has become another important foundation form of offshore wind turbines. The foundation of the suction bucket in shallow water is a bucket structure with a closed top and an open bottom. The installation method of the suction bucket foundation is different from that of the single pile. It needs to sink into the seabed foundation soil to a certain depth by its own gravity to form a closed loop in the cavity; The strong negative pressure makes the suction bucket completely fill the soil layer. Compared with the single pile foundation, less steel is used under the same load, which greatly saves the production cost. Since the horizontal load performance of a single-pile foundation often depends on the shallow soil (about 5~10 times the pile diameter [12]), and the bucket foundation, as a wide and large foundation with a shallow depth of penetration, can be optimized in the shallow soil range. Basic horizontal force mode. Denmark successfully applied suction bucket foundation to offshore wind turbines and wind measuring towers in 2002 and 2009 respectively [13-14]. Relevant Chinese units have also made some effective attempts, and successfully constructed a prototype offshore wind turbine with a suction barrel foundation. At present, the suction bucket foundation is widely used for sandy soil and silt soil with relatively good soil quality, but for areas with poor shallow soil properties (such as the southeastern coastal areas of China), the inclination angle is still too large and the horizontal bearing capacity is insufficient. Stiffness weakened obviously and so on. Therefore, large-diameter monopile foundations are still widely used in the southeastern coastal areas of China to ensure the safety of wind turbines.

Therefore, in order to further enhance the horizontal bearing capacity of the single-pile foundation and make up for the defect that the suction bucket foundation is difficult to exert its bearing capacity in areas with poor shallow soil quality. In recent years, the engineering community has proposed a new type of foundation-large-diameter single pile-barrel combination foundation, as shown in Figure 3. Among them, the barrel body is used as a wide and large foundation with a shallow depth of soil, which is more conducive to the horizontal resistance of the shallow seabed soil. Bearing performance.

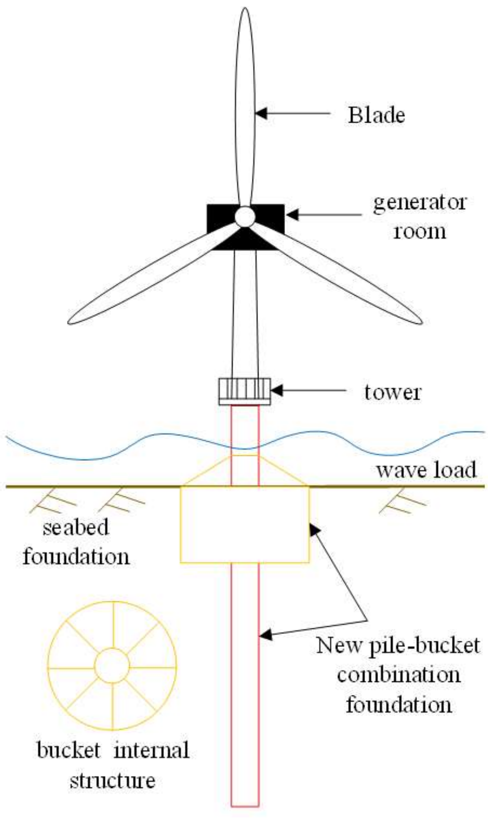

Figure 3. Schematic diagram of pile-bucket combination foundation

ISSN: 2414-1895 DOI: 10.6919/ICJE.202206_8(6).0058

3. Deformation Characteristics and Theoretical Calculation Method of Pile Foundation for Offshore Wind Turbine

3.1 Deformation Characteristics of Pile Foundation for Offshore Wind Turbines

The bearing capacity of a single pile under horizontal static load is mainly the result of pile-soil interaction. The main factors affecting the horizontal bearing capacity of the pile are the deformation characteristics of the soil around the pile and the physical and mechanical characteristics of the pile body. According to elasto-plastic mechanics, the whole process of deformation development of single pile foundation under horizontal static load is divided into three stages: 1) linear elastic stage, 2) elastic-plastic stage, 3) failure stage, which is the first to show on the chart. The initial slope does not change to a straight line, then the slope decreases slowly, and becomes flat after reaching the inflection point. Finally, the horizontal displacement increases and the horizontal load does not increase any more, as shown in Figure 4.

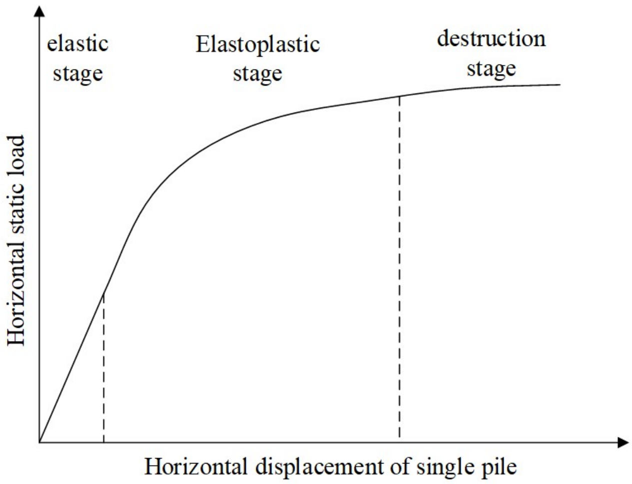

Figure 4. Horizontal load displacement-load curve of pile foundation

The horizontal static load transfers the load to the top of the pile through the loading point. The pile above the soil surface has no resistance, so the load on the top of the pile is transferred to the soil body below the soil surface, and the soil around the pile provides soil resistance to resist the displacement of the pile body. Elastic or plastic deformation of the pile structure. When the horizontal static load applied to the top of the pile is small, the deformation of the pile-soil system is in the elastic stage, and the load-displacement curve increases linearly, and the slope represents the initial stiffness of the pile; with the increase of the horizontal load, the deformation of the pile-soil system is Elastic-plastic deformation, the load-displacement curve shows nonlinear development, and the stiffness of the pile-soil system decreases sharply. After reaching the inflection point, the decreasing trend of the stiffness of the pile-soil system becomes gentle. Usually, the horizontal load value corresponding to the inflection point is used for the pile at this load. The ultimate bearing capacity of the height; then continue to load, the horizontal bearing capacity of the pile foundation reaches the maximum value (the value exceeds the ultimate bearing capacity of the pile foundation), and at this time, the soil around the pile is completely destroyed and the bearing capacity is lost.

3.2 Theoretical Analysis Method of Pile Foundation Force of Offshore Wind Turbine

In order to study the horizontal load response of a single pile in soft clay and obtain the load-displacement curve of the pile and its horizontal ultimate bearing capacity, the following four methods are mainly used at present: 1) elastic foundation reaction force method; 2) ultimate foundation reaction force method; 3) Composite foundation reaction force method (p-y curve method); 4) Elastic analysis method [15-17].

ISSN: 2414-1895 DOI: 10.6919/ICJE.202206_8(6).0058

(1) Elastic foundation reaction force method [18-20]

The elastic foundation reaction force is the reaction force acting on the pile body by the displacement of the pile-soil system. The bending moment of the pile, the deformation of the pile body and the foundation reaction force under the horizontal load are solved by the beam bending theory, which is suitable for rigid piles and flexible piles.

According to the Chinese pile foundation code, the elastic foundation reaction method makes the following assumptions: 1) Using the Winkler foundation soil model, it is assumed that the soil around the pile is a series of discontinuous springs, the pile body is linearly connected to these springs, and the pile-soil system is ignored. 2) It is assumed that the foundation soil has no tensile strength and can only bear the pressure; 3) The excavation resistance at a certain depth changes in direct proportion to the displacement of the pile body.

According to the difference of the assumed foundation reaction coefficient, this method is often divided into Zhang Youling method (the foundation reaction coefficient does not change n=1) and the m value method (the foundation reaction coefficient changes with the depth n≠1), and the commonly used method for highway design in China. The C value method. To sum up, the elastic foundation reaction force method has many assumptions and cannot consider the complex nonlinear problem between piles and soil, so this method is usually used for the analysis of small displacement pile foundations.

(2) Ultimate foundation reaction force method [21-24]

The method assumes the distribution form of the foundation reaction force when the pile-soil system is in the limit equilibrium state, and deduces the foundation soil reaction force through the external load and equilibrium conditions acting on the pile foundation.

The reaction force of the foundation soil is a function of the depth x below the mud surface, and cannot reflect the result of the deformation of the pile body. Therefore, this method cannot be used to calculate the deformation of the pile body under the limit state. It is usually suitable for calculating the ultimate bearing capacity of rigid short piles.

Since Rase first proposed the distribution pattern of the horizontal soil reaction force of the pile foundation changing linearly along the depth, and based on the horizontal load and balance conditions acting on the pile body, the horizontal soil reaction force of the pile foundation under the limit state was solved, and many scholars have proposed Different distribution modes of foundation soil reaction force are presented, and the corresponding limit soil reaction force equation is given.

The ultimate foundation reaction force method is the simplest method in the expression and reaction force distribution diagram among the four theoretical methods, and this method still has major defects, that is, the deformation of the foundation soil is not considered when the horizontally loaded pile reaches the limit state. Therefore, the influence of soil deformation around the pile on the pile-soil system cannot be analyzed.

(3) Composite foundation reaction force method (p-y curve method)

The composite foundation reaction force method is the most widely used method in engineering design at present. The biggest difference between this method and the above two methods is that the nonlinear change of the pile-soil system under horizontal load is considered, and the flexural stiffness of the pile body and the bending stiffness of the pile body can be considered. The change characteristics of the external load are combined with the theoretical solution to deduce the internal force and displacement of the pile body. This method can propose different p-y curves for different soils and pile foundations, and can be well applied to the analysis of rigid piles, flexible piles and rigid-flexible piles under large displacement under horizontal load.

McClelland and Focht[27] first thought that the soil stress-strain curve obtained from the indoor triaxial compression test was related to the resistance-deformation curve of the horizontally loaded pile. Matlock[28] completed the single pile static horizontal load pile test in the soft clay foundation, and obtained the p-y curve of the soft clay. This method is adopted by the American Petroleum

ISSN: 2414-1895 DOI: 10.6919/ICJE.202206_8(6).0058

Institute "Technical Specifications for Design and Construction of Anchored Offshore Platforms" (API-RP2A, 2007) [28] and the DNV specification of Det Norske Veritas [29], and is widely used in the field of engineering design. Followed this method. According to the empirical formulas in API and DNV codes, the horizontal static load, cyclic load p-y curve and the ultimate soil reaction force under the horizontal static load can be obtained in the clay foundation.

After decades of development of the p-y curve, especially in recent years, the number of offshore oil platforms and offshore wind farm projects has been increasing. In addition to the p-y curve used in the above specifications, many scholars at home and abroad have conducted numerical simulations, constant gravity model tests, centrifugal model tests and Field in situ tests have proposed a variety of different pile foundation p-y curves. Georgiadis et al. [30] completed a small-scale model test of a single pile under horizontal static and cyclic loads in soft clay, and believed that the p-y curve proposed by matlock did not consider the effect of the initial stiffness of the pile-soil system when the deformation was small (the displacement is 0, the stiffness is infinite), resulting in an excessively large initial stiffness, which is inconsistent with many later measured p-y curves. Therefore, a static p-y curve in the form of a hyperbola in soft clay is proposed.

Kim[31] completed the horizontal load static test of a single pile in sand, and proposed a hyperbolic p-y curve for the pile foundation suitable for sand. The results show that the hyperbolic p-y curve can better fit the sand. The measured p-y curve around the pile in the soil foundation.

4. Model Test Research on Single Pile Foundation of Offshore Wind Turbine

Model test, as one of the important means to study the horizontal load characteristics of pile foundation in geotechnical engineering, can provide measured data verification for theoretical methods and finite element numerical simulation method, and is an important means of pile foundation horizontal load research. The model test can be divided into full scale test and scale test according to different scales, while the full scale test is usually an in-situ test, so the cost of financial and human resources is large, and the large scale will lead to difficulty in variable control and many inconveniences. prediction problem. Therefore, the in situ full-scale model experiments described in the literature are relatively few compared to the scaled-scale experiments. The scaled physical model test can be divided into the model test under 1g constant gravity and the centrifugal model test. Due to the limitation of the size of the centrifuge, the scale of the centrifugal test is often small, while the 1g constant gravity model test site has small restrictions and can be carried out in large scales. The scale model experiment can more realistically reflect the stress state of the actual engineering soil and the deformation and stress of the pile foundation. In the early stage of model test research on pile foundations, due to the limitation of test conditions, most of them were horizontal static in-situ tests in construction projects. For example, Liu et al. [32], Poulos et al. The load-displacement curve and the horizontal static ultimate bearing capacity of the static horizontally loaded piles were studied by in-situ tests, and the p-y curve of soft clay and sandy soil and the design method of the pile foundation, which were first used in engineering, were proposed. In recent years, with the development of monitoring methods and test instruments, the research content has been greatly expanded.

5. Research on Composite Pile Foundation and Pile-barrel Combination Foundation

The soil depth that contributes the most to the bearing capacity of the horizontally loaded pile foundation is about 5-10 times the pile diameter below the soil surface, which provides an idea for further improving the horizontal bearing capacity of the pile foundation in soft clay. The soil is reinforced. There are few engineering examples of composite piles reinforced with shallow soil, and most of them are studies on the horizontal ultimate bearing capacity.

For composite piles, Weng Yagu et al. [35] studied the horizontal static loading performance of cast-in-place piles in soft soil after high-pressure jetting piles through on-site full-scale hydrostatic loading tests; Wang Anhui et al. [36] based on the existing soft soil The p-y curves of clay and hard clay

ISSN: 2414-1895 DOI: 10.6919/ICJE.202206_8(6).0058

single piles were measured, and the soil reaction force distribution of concrete and cement-soil composite pile foundations under horizontal static load was measured, and the calculation method of p-y curves of SC piles in soft clay was established; Guo Youlin et al. [37] aimed at The bearing characteristics, construction technology and failure mode of the new concrete-gravel tandem composite pile were studied. Therefore, the reinforcement forms of composite piles are changeable, and further research needs to be done according to different working conditions and foundation soil properties.

At present, this new type of pile-barrel composite foundation is still in the design stage, and there are few data in the published literature. In order to study the stress deformation mode and horizontal bearing performance of this new type of foundation, Liu Wenbai et al. [38] established an ABAQUS finite element model, and studied the size effects of pile length, bucket radius and bucket wall height on the downward pressure of pile-bucket composite foundation. Influence of bearing capacity, the optimal size combination of pile length, bucket radius and bucket wall height was obtained. Ding Hongyan et al. [39] used the ultimate foundation reaction force method to propose an approximate calculation formula for the bearing capacity of the pile-bucket composite foundation in clay, and studied the main factors affecting the bearing capacity and deformation of the pile-bucket composite foundation through a numerical model. Wang Jiayu et al. [40] obtained the failure envelope of the pile-bucket composite foundation in the horizontal force-bending moment load space through numerical simulation. Liu Run et al. [41] simulated and studied the force transfer form of the pile-bucket composite foundation, and analyzed the influence of bucket diameter, pile diameter, bucket height, and pile length on the horizontal bearing capacity. Liu Hongjun et al. [42] optimized the barrel size of the pile-barrel composite foundation based on ABAQUS modal analysis, and evaluated the improvement of the bearing performance of the pile-barrel composite foundation compared with the traditional single-pile foundation.

6. Conclusion

To sum up, the new pile-bucket combined foundation enhances the horizontal bearing capacity of the single-pile foundation and makes up for the defect that the suction bucket foundation is difficult to exert its bearing capacity in the shallow soil area. For single piles, the existing model test research prototypes are mostly small-diameter piles, and most of them are small-scale tests, and the obtained p-y curves are not directly applicable to large-diameter pile foundations; for composite piles, the existing model test researches are mostly on-site However, most of them are small-sized pile diameters, which are difficult to apply to large-diameter composite piles used in offshore wind turbines. For the new pile-bucket combination foundation, theoretical analysis and numerical simulation methods have been used to study the pile-bucket combination foundation. There is basically no report on the large-scale model test research of large-diameter pile-bucket composite foundations.

Acknowledgments

The paper is supported by Science and Technology Project of Key topics of Wenzhou Polytechnic (WZYGJzd202103); (WZYCJRH202005).

References

[1] Gong Xiaonan. Pile Foundation Engineering Manual [M]. Beijing: China Construction Industry Press, 1997.

[2] Chen Zhongyi, Ye Shulin. Basic Engineering [M]. Beijing: China Construction Industry Press, 1990.

[3] Huang Haihong, Yang Xiaoping. Basic Engineering [M]. Beijing: China Construction Industry Press, 2008.

[4] Huang Weiping, Liu Jianjun, Zhao Zhanhua. Research status and development trend of offshore wind power infrastructure [J]. Ocean Engineering, 2009, 27(2):130-134.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202206_8(6).0058

[5] Ge Chuan, He Yanping, Ye Yu, Du Pengfei. Development, composition and basic form of offshore wind farms [J]. China Offshore Platform, 2008,23(6): 31-35.

[6] Cater M. North Hoyle offshore wind farm: design and build [C]. Proceedings of the ICE: Energy, 2007:9-21.

[7] MONE C, HAND M, BOLINGER M, RAND J, HEIMILLER D, HO J. 2015 cost of wind energy review[R]. National Renewable Energy Lab, Golden, USA, 2017.

[8] ANDERSEN K H, MURFF J D, RANDOLPH M F. Suction anchors for deep water applications[C]. Frontiers in offshore geotechnics, Perth, Australia, 2005.

[9] China Three Gorges Corporation, Xiangshui Offshore Wind Power Project Construction Technology Summary [R]. 2016.

[10] Doherty P and Gavin K. Laterally loaded monopile design for offshore wind farms[J]. Proceedings of the ICE-Energy, 2011,165(1); 7-17.

[11] General Institute of Water Resources and Hydropower Planning and Design. "Technical Regulations for Foundation Design of Wind Turbine Towers (Trial)" (FD003-2007) [S]. 2007.

[12] He Ben. Horizontal loading behavior of single pile and composite pile foundation in soft clay foundation [D]. Hangzhou: School of Architecture and Engineering, Zhejiang University, 2016.

[13] Houlsby G T, Ibsen L B, Byrne B W. Suction caissons for wind turbines[C]. Frontiers in Offshore Geotechnics: ISFOG, Perth, 2005; 75-93.

[14] Leblanc C. Design of Offshore Wind Turbine Support Structures[D]. Alborg, Denmark; Alborg University. 2009.

[15] Poulos H G, Davis E H. Pile foundation analysis and design[M]. New York: Wiley, 1980.

[16] Reese L C, Van Impe W F, Holtz R D. Single piles and pile groups under lateral loading[M]. Rotterdam: Balkema, 2001.

[17] Fan C C, Long J H. Assessment of existing methods for predicting soil response of laterally loaded piles in sand[J]. Computers and Geotechnics, 2005, 32(4); 274-289.

[18] Reese L C, Matlock H. Non-dimensional solutions for laterally-loaded piles with soil modulus assumed proportional to depth[M]. Association of Drilled Shaft Contractors, 1956.

[19] Matlock H, Reese L C. Generalized solutions for laterally loaded pile[J]. Journal of the Soil Mechanics and foundations Division, 1960, 86(5); 63-94.

[20] Rase P E. Theory of lateral bearing capacity of piles[C]. Proc 1st ICSMFE, 1936; 65-79.

[21] Broms B B. Lateral resistance of piles in cohesive soils [J]. Journal of the Soil Mechanics and Foundations Division, 1964,90(2); 27-64.

[22] Petrasovits G, Award A. Ultimate lateral resistance of a rigid pile in cohesionless soil[C]. The 5th European Conference on Soil Mechanics and Foundation Engineering, Madrid, 1972, 3; 407-412.

[23] McClelland B, Focht Jr J A. Soil modulus for laterally loaded piles[J]. Journal of the Soil Mechanics and Foundations Division, 1956, 82(4);1-22.

[24] MATLOCK H. Correlations for design of laterally loaded piles in soft clay[C]. The II Annual Offshore Technology Conference, Houston, Texas, 1970; 577–594.

[25] American Petroleum Institute (API). Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms-Working Stress Design[R]. 2007.

[26] Veritas D D N. DNV-OS-J101 offshore standard[J]. Design of Offshore Wind Turbine Structures, 2010.

[27] Georgiadis M, Anagnostopoulos C, Saflekou S. Cyclic lateral loading of piles in soft clay[J]. Geotechnical engineering, 1992, 23(1).

[28] Kim B T, Nak-Kyung Kim, Woo Jin Lee, Young Su Kim. Experimental load-transfer curves of laterally loaded piles in Nak-Dong River sand [J]. Journal of Geotechnical and Geoenvironmental Engineering. 2004; 416-425.

[29] Liu H L, Chu J, Deng A. Use of large-diameter, cast-in situ concrete pipe piles for embankment over soft clay[J]. Canadian Geotechnical Journal, 2009,46(8); 915-927.

[30] Poulos H G. The behavior of Laterally Loaded Piles I. Single Piles[J]. Journal of Soil Mechanics and Foundations Div. 1971.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202206_8(6).0058

[31] Dunnavant T W. Experimental and analytical investigation of the behavior of single piles in overconsolidated clay subjected to cyclic lateral loads[D]. Houston; University of Houston, 1986.

[32] Weng Yagu, Wang Huan, He Ben, Chen Guoxing. In situ experimental study of horizontal static load of pile foundation after high-pressure jetting pile reinforcement [J]. Highway Traffic Technology, 2015, 5; 49-52.

[33] Guo Youlin, Zhao Minghua, Peng Wenzhe. Bulging deformation and settlement analysis of solid-discrete tandem composite piles based on improved strain wedge model [J]. Chinese Journal of Geotechnical Engineering, 2019, 41(11): 2149-2154.

[34] Liu Wenbai, Wang Dashan, Zhao Long. Design and Numerical Simulation of Pile-Barrel Foundation Structure under Downward Loading [J]. Chinese Journal of Geotechnical Engineering, 2010, 32(S2): 216-219.

[35] Ding Hongyan, Hu Caiqing, Zhang Puyang, Zhu Dongjian. Analysis of horizontal bearing performance of pile-tube composite foundation in single-layer clay [J]. Ocean Engineering, 2014, 32(2): 30-37.

[36] Wang Jiayu, Liu Run, Li Baoren, Lian Jijian, Ding Hongyan. Study on the bearing capacity envelope of H-M load space of pile-tube composite wind power foundation [J]. Journal of Hydraulic Engineering, 2015, 46(S1): 354-359.

[37] Liu Run, Li Baoren, Lian Jijian, Ding Hongyan. Research on the joint bearing mechanism of piles and cylinders for single-pile composite tubular foundations for offshore wind power [J]. Journal of Tianjin University (Natural Science and Engineering Technology Edition), 2015, 48(5) : 429-437.

[38] Liu Hongjun, Zhang Peng, Wang Quandi, Yang Qi. Structural optimization and bearing performance analysis of pile-and-tube composite foundation [J]. Journal of Harbin Engineering University, 2018, 39(7): 1165-1171.