Research on the vertical compressive bearing characteristics of offshore wind power steel pipe piles

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Abstract: In the absence of a comparison of static load test results for large-diameter steel pipe piles at home and abroad, optimize the design parameters based on the test pile results to guide later construction. This paper is based on the pile foundation design calculation method of API specification, as well as the relationship between the t-z, Q-z, p-y curve modes suggested by this specification, vertical ultimate bearing capacity, and stratum parameters. The conclusions and results obtained are limited to pile foundation calculations using API specifications. Analyze and back-analyze the results of static load tests on large-diameter steel pipe piles, and verify the pile foundation parameters. Combined with the data obtained from the test pile tests, analyze the stratum parameters to guide the optimization design of pile foundations in the construction drawing design stage of the offshore wind farm expansion project.

Keywords: Pile test results, Compressive bearing characteristics, Static load test, Steel pipe pile parameters

1. Introduction

Offshore wind power projects have large spacing between wind turbine locations, generally ranging from 0.8 to1.2km, with significant differences in the ground conditions[1,2]. It is not advisable to use the bearing capacity obtained from static load tests of a certain pile location for the entire planning area design. It is necessary to combine the engineering geological conditions, analyze the bearing characteristics and parameters of the pile foundation through reverse analysis based on current relevant specifications and standards, and compare them with the previous geological parameters, design parameters, and calculation results to guide the optimization design of pile foundations in the construction drawing design phase[3,4]. The research on the results of the pile test in this paper is based on the current calculation methods introduced by the American Petroleum Institute (API) in the petroleum industry, analyzing the vertical compressive bearing force mechanism and characteristics of the pile foundation, and proposing suggestions for calculating the bearing capacity of large-diameter steel pipe piles based on the results of the pile test. Based on the results of the pile test, the vertical compressive bearing characteristics and mechanism of steel pipe piles are analyzed, differences between calculated values and measured values are compared, and suggestions for pile foundation parameter values are proposed[5,6].

2. Pile test analysis content

2.1 Pile layout and test content

Vertical compressive bearing characteristics of steel pipe piles. Analyze the vertical compressive bearing mechanism of large-diameter steel pipe piles, study the calculation method of vertical compressive ultimate bearing capacity, refer to the t-z and Q-z curve patterns recommended by API specifications, as well as the relationship between vertical compressive ultimate bearing capacity and stratum parameters[7,8]. Combined with the vertical compressive static load test data of test piles, analyze the stratum parameters and propose suggestions for the values of pile compressive parameters. Complete the vertical compressive static load tests of S1 and S2 test piles.

The experiment is set up with 6 anchor piles and 2 test piles. All test piles and anchor piles have the same diameter, where S1 and S2 test piles are open-ended steel pipe piles used for axial compression, axial pull-out, and horizontal static load tests. The M1 to M6 anchor piles provide reaction force for the test loading system. (Figure 1)

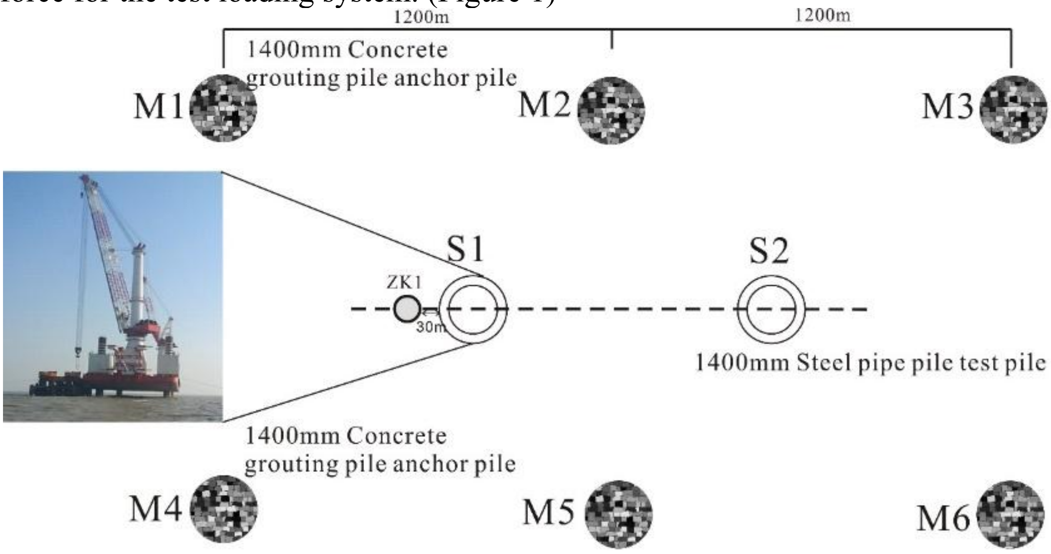

Figure 1 Layout diagram of test pile positions and photos of test piles

2.2 Stratigraphic Content

According to the stratigraphy revealed by drilling, the sediments within the exploration depth are all Quaternary deposits. The upper part consists of fine sand, silt, and layer-like muddy silt clay (① layer, ② layer, ③-1a layer, ③-Clamp1 layer) deposited in the Holocene (Q4) coastal and shallow marine environments. The lower part consists of clayey silt, fine sand, and fine sand (④-1 layer, ⑥-1layer, ⑥-3layer) deposited in the Late Pleistocene (Q3) estuarine to coastal environments. The site exploration depth can be divided into 5 engineering geological layers, further subdivided into 6 engineering geological sub-layers and 1 interlayer. The elevation of test pile S1 passes through the thick-33.12m，⑥-1 layer to enter the fine sand （3.6m）of the ⑥-3 layer the thick-0.6m; the elevation of test pile S2 enters the fine sand of the ⑥-1 layer the thick-4.2m.

3. Vertical Compression Bearing Characteristics of Steel Pipe Piles

3.1 Vertical Compression Bearing Mechanism of Steel Pipe Piles

To evaluate the vertical bearing capacity characteristics of open-end pipe piles, it is necessary to correctly understand the formation of soil plugs and their impact on the vertical bearing performance of the foundation piles. When the soil plug is completely closed, the calculation formula for the ultimate vertical bearing capacity Qt of a single pile under compression is as follows:

$$Q_t=Q_{so}+Q_{dw}+Q_{dq}-W_p \tag{1}$$

On the contrary, for incomplete closure of the soil plug, the calculation formula for the ultimate bearing capacity Qt of a single pile under vertical compression

$$Q_t=Q_{so}+Q_{dw}+Q_{si} \tag{2}$$

Qt ——Pile vertical compressive ultimate bearing capacity (kN);
Qso——Ultimate external frictional resistance provided by the soil outside the pile (kN);
Qsi——Ultimate internal frictional resistance provided by the soil inside the pile (kN);

Qdw——Ultimate ring end resistance of pile end soil acting on the steel ring area As at the pile end (kN);

Qdq——The ultimate end resistance of the soil plug acting on the inner circular area A q at the pile end (kN);

Wp ——Effective gravity of soil in pile (kN).

The right side of the above two equations can be divided into two parts. The first part is Qso + Qdw, which represents the ultimate lateral friction resistance of the pile and the ultimate end resistance of the soil layer at the pile toe circle; the second part is then calculated based on the closure state of the soil plug, either the ultimate internal friction resistance of the soil plug or the ultimate end resistance of the soil plug.

3.2 Vertical Compression Ultimate Bearing Capacity

The calculation formula for the vertical ultimate bearing capacity of open-ended steel pipe piles in the API specification：

$$Q_t=Q_s+Q_d=f\cdot A_u+q\cdot A_g \qquad (3)$$

Qt ——Vertical compressive ultimate bearing capacity of steel pipe pile (kN);

Qs ——Maximum lateral friction force (kN);

Qd ——Ultimate end resistance (kN);

f ——Unit side friction resistance (kPa);

Au ——pile outer surface area（m2）；

q ——Unit end bearing capacity (kPa);

Ag —— pile end total area（m2）.

4. Soil Arching Effect and Displacement-Load Curve

Based on the pile body strain and displacement distribution under each level of load obtained from the test pile, as well as the unit side friction resistance of the pile and the end resistance of the pile, combined with the recommended axial load-displacement transfer curve in the code (referred to as the t-z curve, i.e., the pile side shear stress-pile-soil relative displacement curve) and the pile end load-displacement curve (referred to as the Q-z curve), the load-displacement curve of the test pile is analyzed.

4.1 Lateral displacement of anti-pressure pile and external frictional resistance between pile and soil

According to the recommended typical t-z curve model for cohesive soil and the derived z/d values of cohesive soil layers, as well as the z values of sandy soil layers, the external frictional resistance of the soil at the outer surface of test pile S1 under various levels of vertical load is obtained, as shown in Figure 2.

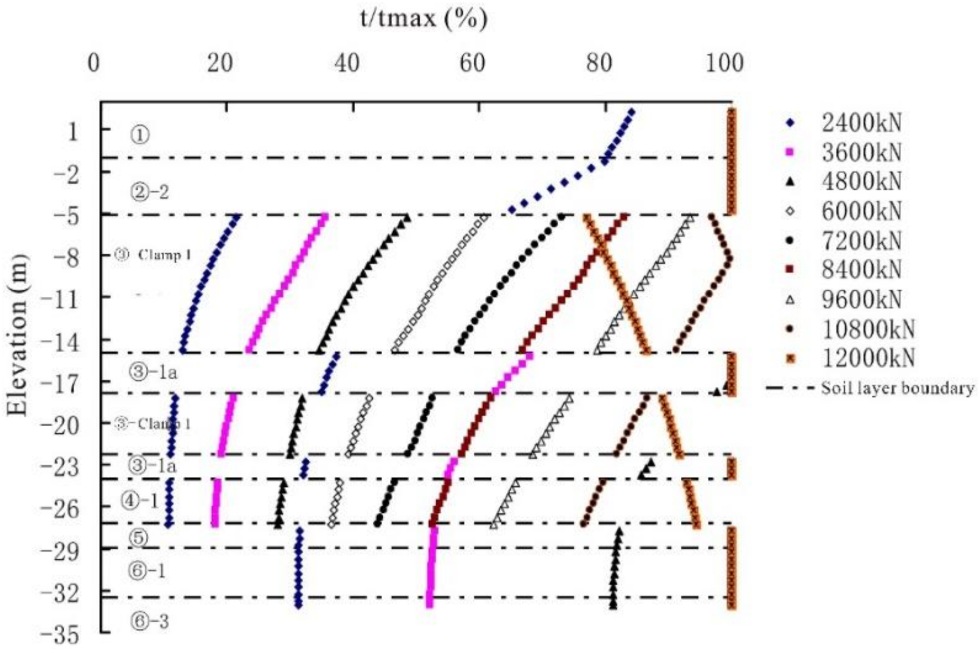

Figure 2 External frictional resistance of pile soil interface under various levels of vertical load (S1 test pile)

Based on the displacement Z generated at the pile end under each level of load obtained from the pile load test, the ratio of Z to the pile diameter d is obtained. According to the recommended pile end load-displacement (Q-z) curve model in the specification, the pile end resistance of the S1 test pile is obtained, with a pile diameter of 1400mm as shown in Table 1.

Table 1 Pile end displacement z, z/d value and pile end resistance under load action

Compressive load（kN）	2400	3600	4800	6000	7200	8400	9600	10800	12000
Pile displacement z（mm）	0.02	0.06	0.32	1.08	1.61	2.83	4.69	7.38	16.09
z/d	14×10^{-6}	43×10^{-6}	229×10^{-6}	771×10^{-6}	115×10^{-5}	2021×10^{-6}	335×10^{-5}	5271×10^{-6}	1493×10^{-5}
End resistance（%）	0.02	0.05	0.29	0.96	1.44	25.05	28.07	32.44	46.57

From the table, it can be seen that according to the recommended Q-z curve pattern, the end resistance of the test pile gradually increases with the increase of the load. According to the recommended t-z curve pattern, t is the frictional resistance at the interface between the pile and the soil, while the pile report provides the side frictional resistance of the pile, which includes the internal and external interface frictional resistance of the pile and the soil. The frictional resistance at the interface between the pile and the soil must be separated before fitting the t-z curve.

According to the Q-z curve pattern suggested by the specifications, Q is the end resistance of the soil at the pile end acting on the total cross-sectional area of the pile base, including two parts: the end resistance on the pile base ring area and the soil plug end resistance, which is different from the pile end resistance provided by the pile test results that only include the ring end resistance. Therefore, the pile end resistance provided by the pile test results needs to be included in the soil plug end resistance for fitting the Q-z curve. See Figure 3 for the results.

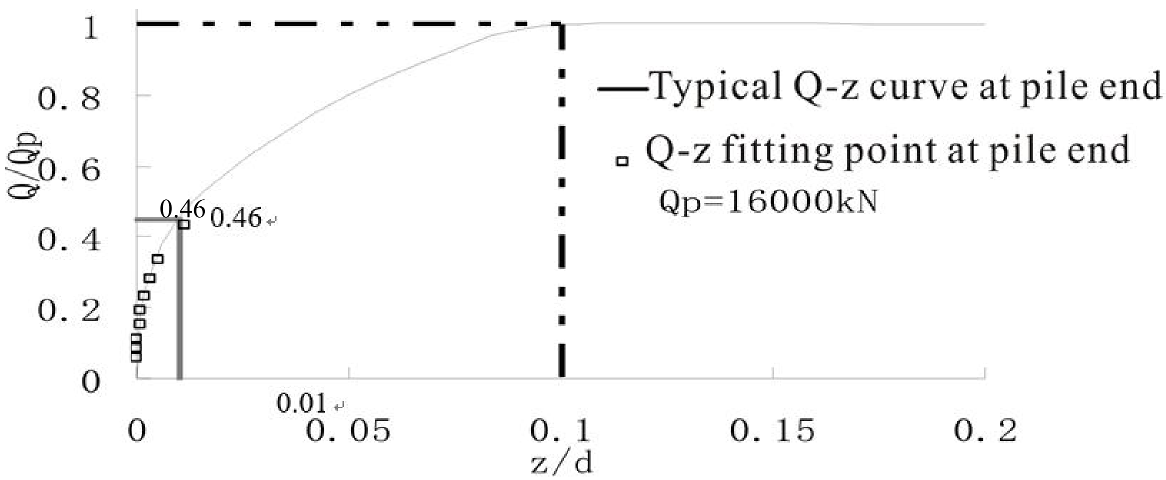

Figure 3 Fitting of Q-z curve at pile end

4.2 Analysis of Steel Pipe Pile Parameters

Based on the comprehensive geological survey results, the analysis of the horizontal bearing characteristics of the subsequent steel pipe piles, and the pile foundation calculation method recommended by the API specification, the parameters of the vertical compressive steel pipe piles are shown in Table 2. The unit pile side frictional resistance f and the overlying effective soil pressure in each stratum. See Figure 4

Table 2 Vertical Compression Steel Pipe Pile Parameters

Number	Stratum	Effective weight	Pile soil friction angle δ	Limit value of surface frictional resistance	Limit value of unit end resistance	Bearing capacity coefficient
		kN/m3	°	kPa	kPa	-
①	Silty sand	9.6	15	47.8	1900	8
②-2	Silt	9.3	18	59.3	2500	10.4
③-Clamp1	Silty clayey loam	8.1				
③-1a	Silty sand	9	28	89.9	7680	32
④-1	Silty clay	8.1				
⑤	Silty soil mixed with silty clay	9	22	72.7	3660	15.2
⑥-1	Silty sand	9.1	30	95.7	9600	40
⑥-3	Fine sand	8.5	33	107.2	11040	46

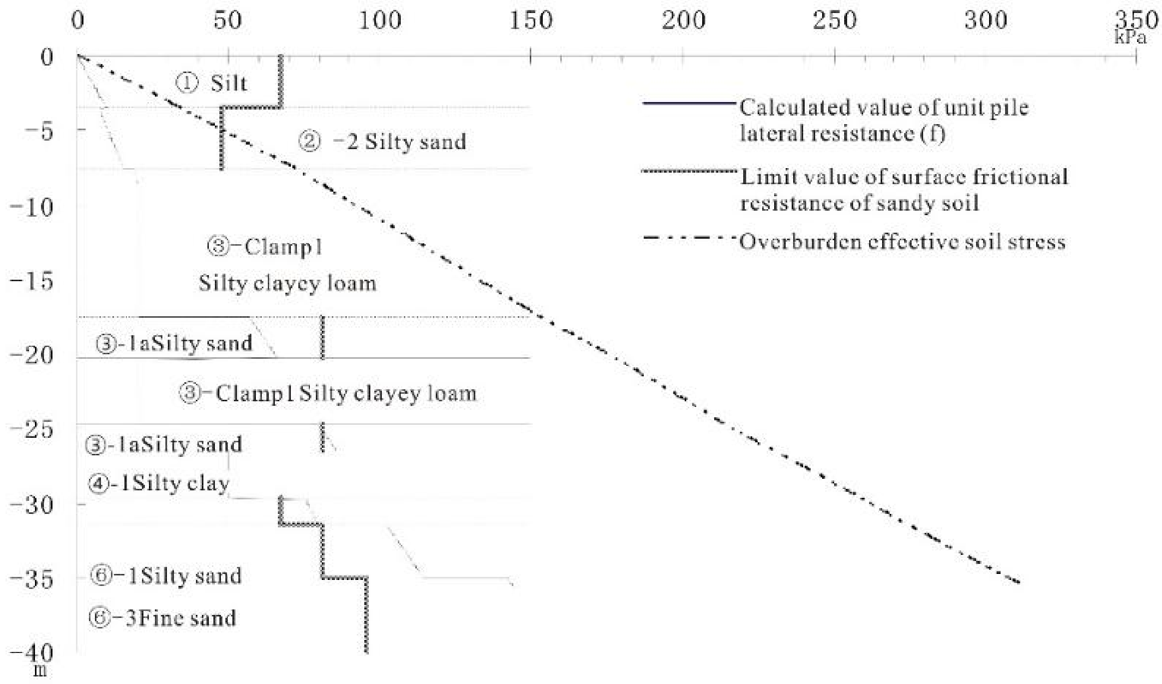

Figure 4 Side friction resistance of various strata units and overlying effective soil pressure

It can be seen that the calculated value of the side resistance f of the sand layer unit pile above the burial depth boundary is less than the recommended limit in the code, so the calculated value should be taken; while the calculated value of f below is greater than the limit, so the limit value should be taken.

Two methods are used to estimate the inner side friction resistance of the pile in the calculation: estimation by multiplying the outer side friction resistance by the coefficient ξ; estimation by reducing the coefficient η based on the soil plug effect. The values of η and ξ are determined based on the calculation results and combined with similar engineering experience in the local area, with ξ values of 0.55, 0.60, and 0.65, and η values of 0.15, 0.20, and 0.25 for analysis. The analysis of the vertical ultimate compressive bearing capacity of steel pipe piles is shown in Table 5. The comparison of the calculation results with the test pile results is shown in Table 6.

Table 5 Analysis of Ultimate Bearing Capacity of Steel Pipe Piles under Vertical Compression

The mean of unit side friction (f)		① Extreme outer resistance	② Limit cycle end resistance			④ Ultimate compressive bearing capacity
Layer	kPa	kN	kN			kN
①	3.7	6730	1051			④=①+②+③
②-2	13.8					
③-Clamp1	29	③Inner resistance （KN）	ξ	0.55	3701	11483
③-1a	80.1		ξ	0.6	4038	11819
④-1	55		ξ	0.65	4374	12156
⑤	72.7		η	0.25	3197	10978
⑥-1	95.7		η	0.3	4047	11828
⑥-3	107.2		η	0.35	4896	12677

Table 6 Comparison between the calculated vertical compressive ultimate bearing capacity of pile foundation and the test pile results

Content(KN)		Calculated value（kN）				Test pile data（kN）
①	Extreme outer resistance	6730				
②	Inner resistance	ξ	ξ	η	η	
		0.6	0.65	0.3	0.35	
		4038	4374	4047	4896	
③=①+②	Extreme outer resistance	10768	11104	10777	11626	9453
④	Limit cycle end resistance	1051				2547
⑤=③+④	Ultimate compressive bearing capacity	11819	12156	11828	12677	12000

From the results in the table, it can be seen that when the ratio coefficient ξ of the inner side resistance to the outer side resistance is set to 0.6, or when the soil plug effect reduction coefficient η is set to 0.3, the calculated value of the ultimate frictional resistance is slightly greater than the experimental value, the calculated value of the ultimate end bearing resistance is slightly less than the experimental value, and the calculated value of the compressive ultimate bearing capacity is basically consistent with the measured value.

5. Conclusion

According to the t-z curve pattern recommended by the specifications, under a test load of 12000kN for S1 test pile, the skin friction on the outer side of the steel pipe pile is fully mobilized in each stratum. In cohesive soil layers, due to softening of the pile-soil interface strain, the skin friction on the outer side of the pile decreases to about 90%. According to the Q-z curve pattern recommended by the specifications and combined with engineering experience analysis, under a test load of 12000kN for S1 test pile, when the steel pipe pile is supported by layer 6-3 at the pile end, the end resistance of the pile (including the soil plug end resistance) has already reached about 90%.

Using the recommended method to analyze the vertical compressive bearing capacity of steel pipe piles, the soil plug effect needs to be considered. According to the results of the S1 test pile, the ratio coefficient of inner resistance to outer resistance ξ can be taken as 0.60, or the soil plug effect reduction coefficient η can be taken as 0.30. The vertical compressive ultimate bearing capacity of the S1 test pile estimated by the code is 12300kN, and the vertical compressive ultimate bearing capacity of the S1 test pile measured by static load test is 12000kN, which can be used for design reference and should consider a certain safety margin.

References:

[1] Lü Fanren, Chen Renpeng, Chen Yunmin, et al. Field tests on compression and uplift behavior of micropiles in soft ground [J]. China Civil Engineering Journal, 2005, 38(3): 99-105. (in Chinese)

[2] Han J, Ye S L. A field study on the behavior of micropiles in clay under compression or tension [J]. Canadian Geotechnical Journal, 2006, 43(1): 19-29.

[3] Cao Zhaohu, Kong Gangqiang, Liu Hanlong, et al. Model tests on pipe pile penetration by using transparent soils [J]. Chinese Journal of Geotechnical Engineering, 2014, 36(8): 1564-1568. (in Chinese)

[4] Cao Zhaohu, Kong Gangqiang, Wen Lei, et al. Visualization model test on tapered pipe pile installation and pile tip grouting process [J]. Journal of Railway Science and Engineering, 2017, 14(5): 922-927. (in Chinese)

[5] Jori Osterberg.New Device for Load Testing, Driven Pile and Drilled Shaft Separates Friction and End Bearing.Piling and Deep Foundation[J].Netheriands:1989.421-427.

[6] Huang Feng, Liu Chaogang, Li Guangxin, et al. Discussion on the determination method of pile bearing capacity [D]. Journal of Tsinghua University,1998,38(1):28-32

[7] Byrne B W,McAdam R,Burd H,et al. New design methods for large diameter piles under lateral loading for offshore wind applications[C]Third International Symposium on Frontiers in Offshore Geotechnics,Oslo,2015.

[8] Tak Kim B,Kim N-K,Jin Lee W,et al. Experimental load–transfer curves of laterally loaded piles in Nak-Dong River sand[J]. Journal of Geotechnical and Geoenvironmental Engineering,2004,130 (4): 416-425