

Optimization Analysis of Mono-pile Foundation for Offshore Wind Turbine Based on ANSYS Zero-order Method

ZHAO Ming-jie^{*1}, HE Ye², HU Dan-ni³

^{*1}Key Laboratory of Hydraulic and Waterway Engineering of the Ministry of Education, Chongqing Jiaotong University, Chongqing, 400074, China

²School of Civil Engineering, Hunan City University, Yiyang 413000, Hunan, China

³Guangdong Ocean University, Guangdong, 524088, China

^{*1}m.j.zhao@163.com; ²heye.1984@163.com; ³15223442385@163.com

Abstract-Mono-pile foundation of offshore wind turbine was simulated using ANSYS finite element software, conducted quasi-static analysis of the foundation of the offshore wind turbine considering the interactions of environmental load, such as wind, wave, current, etc, optimized the size of the pile based on zero-order method. The wall thickness of the pile was reduced under the premise of ensuring displacement, stress, and stability requirements, the total volume of the pile foundation decreased by 33.5% in order to reach the aim of light-duty design; Combining with the variation of the objective function, design variable and state variable in optimization process, proposed that the displacement of pile top is the primary limiting condition, the optimization of shape topology should be taken into consideration while designing the structure; The wall thickness in some parts of the pile foundation can be appropriately reduced to make full use of the strength of the material, under the premise of ensuring top pile displacement.

Keywords- Offshore Wind Turbine; Mono-pile Foundation; Zero-order Optimization Method; Size Optimization

I. INTRODUCTION

As a heating program of developing the Low-Carbon Economy, offshore wind power generations have been a dramatic growth recently. Compared with onshore wind power generations, it is a invest project of high risks, due to its very complex and harsh marine environments. How to reduce the cost has yet remained the principal aim of the offshore wind power generations, even in the future. According to related data, based cost accounts for nearly 15 to 25 percent of the whole project of the wind power generation. In this sense, designing a secure, rational and economic foundation will be one of the key points of decreasing the cost of developing offshore wind power generations.

With the importance of offshore wind turbine foundation and the complexity of the operating environment, many researchers have investigated the optimization design of wind turbine structures: Yoon G [1] and his partners reliability analysis of offshore wind mono-pile foundation, using response surface method. The basic concept of RSM is to approximate the limit state boundary using an explicit function of the random variables. The design load is difficult to determine with complex operating environment, Agarwal P [2] and others have extrapolation to predict and calculate the occurrence probability of extreme loads, studied structural optimization design process considering extreme loads based on reliability principle; Torcinaro M [3] and others came up with a preliminary optimization process after taking the corresponding limit state of the environment load to the structure of offshore wind turbine into consideration. Bontempi F [4] commented on the safety of offshore wind turbine under complicated circumstances by building numerical models, who guided the mechanism design appropriately. As for domestic scholars, Kang Haigui [5, 6] and others recommended an optimized design of offshore wind turbine based on reliability, later employed finite element software to optimize the connection piece between the foundation and upper grouting section. Yangchao [7] and Xuan Caiyun [8] researched on the mechanism design of the

mono-pile foundation for an offshore wind turbine. Yanyun [9] researched the method of mechanism design based on the parameter design language of the ANSYS. Previous studies use of structural reliability principle to optimize the design, but affected by complex environments and loads, performing reliability analysis of a mono-pile foundation using nonlinear p-y curves is difficult since the limit state functions (LSF) of pile head deformation and rotation angle of pile are in implicit forms. And according to existing design specifications, offshore platform structure in our country applies the method of repeated “trial calculation-verification-modification”, it requires amount of personal resources and time, and the design scheme acquired will not absolutely the best one, thus a powerful assistant tool is badly needed to be introduced into the optimization process of the offshore wind turbine.

Since the value range of state variables and design variables constrain the design, the structural optimization problem becomes constrained optimization problems, when using the general method for structural optimization design. On the contrary, zero-order optimization method as an optimized design method built-in ANSYS, that constrained optimization problem can be transformed into a non-constrained optimization problem, by approaching the objective function and state variable, which greatly simplifies the calculation. Existing data show that ANSYS zero order optimization methods had been applied in the cable structure for cable force calculation [10, 11]. This method is also used to study mechanical structure size optimization [12]. However, the zero-order optimization method rarely applied in respect of offshore wind turbines optimization. Based on this, this paper conducted size optimization for the mono-pile foundation for offshore wind turbine and analyzed the optimized results on the basis of the optimized method of zero-order and finite element software of ANSYS.

II. PRINCIPLE OF THE ANSYS ZERO-ORDER METHOD

Zero-order method requires the numerical value of the dependent variable, rather than the information of its derivative. First of all, fitting the approximate value of the objective function and state variable through least square at zero order optimization; then transferring the stressed optimization problems into unstressed ones by penalty function, the optimization process is delivered on the approximate penalty function until it gets a convergent solution. Therefore, it is called the direct method, which is used to deal effectively with majority engineering problems. ANSYS zero-order method was built on the approximate basis of objective function and state variable, at the beginning of the design, certain initial data of variable is required. The initial data can be directly generated in line with other optimization tools and methods, or randomly generated. In zero-order method, the initial data are sampled certain times, then fitting the corresponding function of the dependent variable and objective function to seek for the optimal solution, as a result it can also be called sub-problem method.

In the optimization process, objective function and variable state formula are approximately treated, the stressed problems are transformed into unstressed ones via penalty function, and further optimized, as the zero-order method shows:

$$\min F(X, p_k) = f + f_0 p_k \left[\sum_{i=1}^n X(x_i) + \sum_{i=1}^{m_1} G(g_i) + \sum_{i=1}^{m_2} H(h_i) + \sum_{i=1}^{m_3} W(w_i) \right]$$

x_i : design variable; g_i, h_i, w_i : state variable; $X(x_i)$: penalty function in line with design variable $G(g_i)$, $H(h_i)$ and $W(w_i)$: penalty function in line with state variable; $F(X, P_k)$: response surface function related with design variable and response surface parameters; f : objective function; P_k : response surface parameters.

In each iterative calculation, the method of SUMT, an optimized technology of unstressed series, is adopted to calculate $F(X, P_k)$, where: k representative sub-iteration, when the sub-problem solving, In order to ensure of the convergence as accurate as possible, the values of P_k : increases with the sub-iterative. All the penalty functions are belong to the inner stretch type, can use SUMT method to search for unconstrained objective function, after transformed into unconstrained problem.

III. MODEL ESTABLISHMENT AND OPTIMIZATION

A. Engineering Background

This paper based on the Rudong County coastal and tidal zone wind farm construction project in Jiangsu Province. In the ocean environment, the bigger the wave, the most adverse impact on the offshore wind turbine structures. Given this, we selected some characteristic wave elements from the wave data in engineering seas, to calculate the wave load of the structure. They are as follows: the design depth of water $h=20\text{m}$, wave height $H=4.2\text{m}$, period $T=6.2\text{s}$. To simplify the calculation model, we assume that the wave is incident along the X-axis and the angle of incidence is 0° . The foundation of the offshore wind turbine constructed by the steel-pipe pile (Q345), whose initial sizes are as follows in the Table 1.

TABLE 1 INITIAL SIZE OF THE STRUCTURE

Units: m

Pile Length	Pile diameter	Pile Wall Thickness	Embedded Depth	Water Depth
83	5	0.06	53	20

B. Loading and Constraint Condition

To analyze the bearing capacity of the mono-pile foundation, we take into account that it is under the extreme condition, which refer to the different loads combination such as wind loading, wind turbine operation loading and wave loading and so on. On this basis and considering a factor of safety of 1.35, the wind loading and wind turbine operation loading were converted into concentrates that act on the flange at the top of the steel pipe pile. The coordinate system of the concentrates after conversion is shown in Fig. 1, and the values of the concentrates are shown in the Table 2. Also, the wave loading is simulated with Element PIPE59 which is the ANSYS comes with and specifically for calculating wave forces.

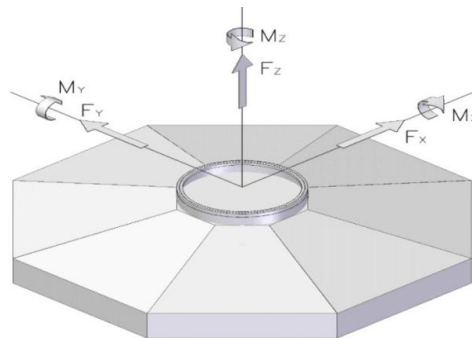


Fig. 1 Coordinate System of wind turbine loads

TABLE 2 LOAD OF THE OFFSHORE WIND TURBINE GENERATORS

Lode Case	FX (KN)	FY (KN)	FZ (KN)	MX (KN m)	MY (KN m)	MZ (KN m)	Safety Factor
Carrying Capacity in Ultimate Limit State	1288	164	-5059	1887	115181	1592	1.35

Presently, Study on the interaction of piles and soil is a complicated problem. To simplify calculating, this paper uses the assumption that the base of the pile was fixed vertically. And then according to engineering geological data, the parameters of the relationship between the horizontal earth resistance and the pile foundation deflection are calculated by p-y curve method, which are used in Element COMBINE39 to simulate the lateral action relationship between the piles and soil.

C. Model Establishment

Common pile foundation for an offshore wind turbine includes mono-pile foundation, single column tri-pile and jacket foundation, etc. This paper mainly builds the FEA modal of the mono-pile foundation based on finite element software and

conducts the optimized analysis. Previous studies show that it will be better that using element PIPE59 to simulate the force on the components in the seawaters, including the wave and current, based on ANSYS software platform. The pile foundation of an offshore wind turbine was comprised of two parts, up and under the water, the latter also includes rock-socket section and flooding parts. In the FEA modal, the rock-socket part of the pile foundation is simulated by element PIPE16, and flooding parts by element PIPE59. The simplified mode and finite element model were shown in Fig. 2.

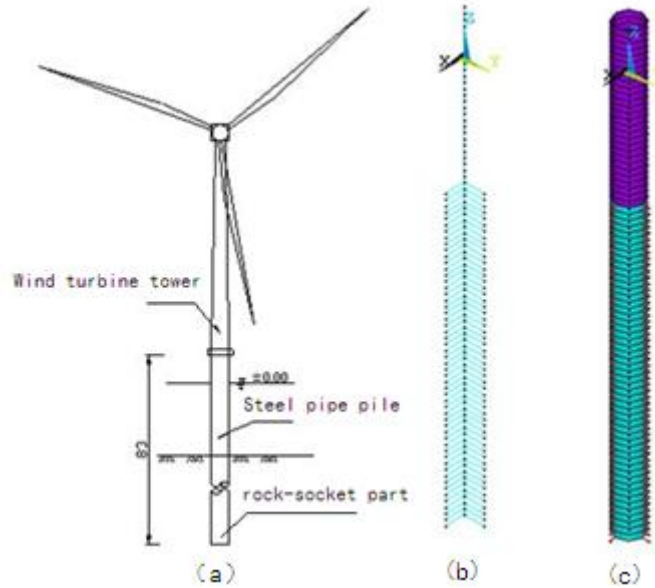


Fig. 2 Simplified Model and Finite Element Model of the Mono-pile Foundation Structure

D. Optimization Process

Using ANSYS parametric design language (referred to as APDL) to achieve optimal design, based on ANSYS zero-order optimization method, and the basic three parameters include: design variables, state variables and objective function. The state variables and objective function can be created in the post-processing module at the end of static seeks a solution. Pile outside diameter D and the thickness t were used as design variables, and pile minimum total volume V as the objective function, in the process of pile foundation size optimization. The constraints include the strength constraint, stiffness constraints, stability and geometric constraints. The first three constraints were processed in by specific provisions of the design specification, the geometric constraints are the upper and lower limits of design variables. The mathematical model for optimization calculation is as follows:

$$\text{Find} : D, t$$

$$\text{Min} : V = \frac{\pi}{4} L \left[D^2 - (D - 2t)^2 \right]$$

$$\text{S.T.} : \begin{cases} \sigma_{\max} \leq [\sigma] \\ \tau_{\max} \leq [\tau] \\ \lambda_{\max} \leq [\lambda] \\ D_l \leq D \leq D_u \\ t_l \leq t \leq t_u \\ |U_{\max}| \leq U \end{cases}$$

D : pile diameter; t : steel pipe pile wall thickness; V : total volume; L : pile length; $\sigma_{\max}$, $[\sigma]$: pile maximum normal stress and structural allowable normal stress; $\tau_{\max}$, $[\tau]$: pile maximum shear stress and structural allowable shear stress; D_u , D_l : upper and lower limits of pile diameter; t_u , t_l : upper and lower limits of pile wall thickness; $U_{\max}$, U : maximum displacement of the pile and the upper limits.

E. Optimization Results Analysis

As the optimization is over, the comparison result of the related parameter values before and after optimization is listed in Table 3. Obviously, after optimization, the design size changes, the cross sectional area decreases as well, the optimal result is the decrease of the thickness of stake wall, under the premise of ensuring displacement, stress and stability requirements, what ultimately makes the weight of the pile reaches weight reduction purposes.

TABLE 3 RESULTS OF SIZE OPTIMIZATION

Parameters	Symbol	Unit	Parameter Values	
			Before	After
Total volume	V	m^3	77.2478	51.3663
Pile Diameter	D	m	5.00	4.96
Pile Wall Thickness	t	mm	60.00	40.06
Maximum Yield Stress	$\sigma_{Q \max}$	MPa	124.21	185.63
Maximum Normal Stress	$\sigma_{\max}$	MPa	117.67	177.80
Maximum Shear Stress	$\tau_{\max}$	MPa	28.49	46.73
Maximum Displacement	$U_{\max}$	cm	13.63	19.98
Fineness Ratio	λ		32.06	32.15

Seen from the results in Table 3, the pile diameter does not change a lot before and after optimization. Hence, it is necessary to study the changes of the parameters in the optimization process. The change law of objective function, design variables (includes pile diameters and pile wall thickness), and state variables (includes stress, maximum displacement of pile top and fineness ratio) in the optimization process with the change of the times of iterative calculation are shown in Fig. 3 to Fig. 8.

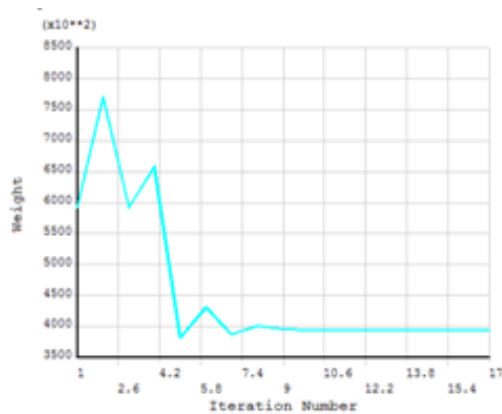


Fig. 3 Change Law of Objective Function

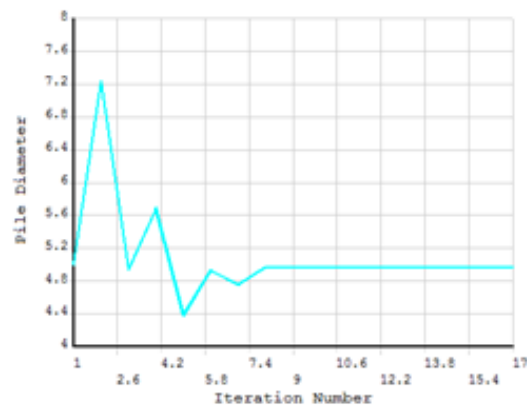


Fig. 4 Change Law of Pile Diameters

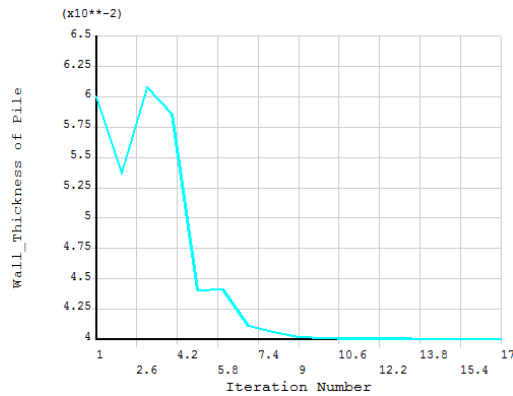


Fig. 5 Change Law of Pile Wall Thickness

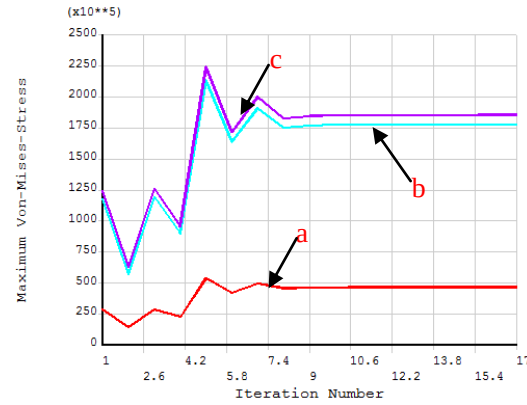


Fig. 6 Change Law of Pile Stress

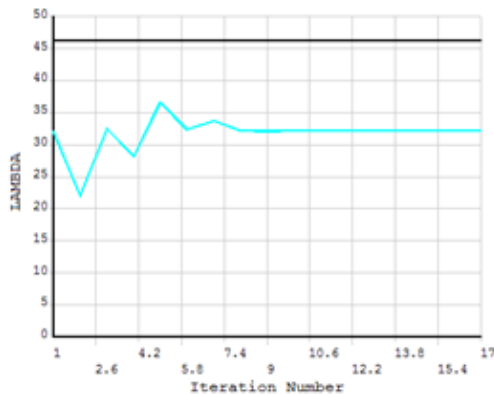


Fig. 7 Change Law of Finenes

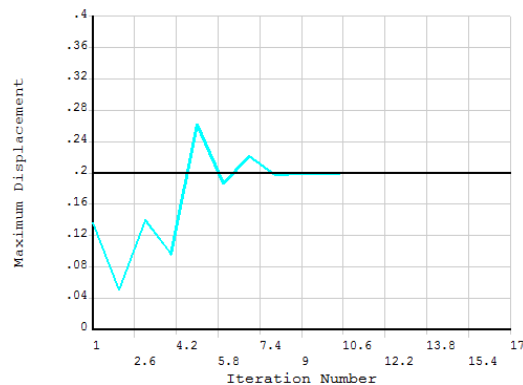


Fig. 8 Change Law of Pile Top Maximum Displacement

The design variables before optimization were substituted into an objective function for iterative calculation, the system-default minimum volume of the pile can be founded. Change law seen from Fig. 3 to 5, the calculation curve of objective function tends to be slow after 7 times iterative calculations, corresponding pile diameter and pile wall thickness reached the optimal situation the system defaulted, with the pile wall thickness reduced about 20 mm, and the total volume of the pile foundation decreased by 33.5%. There are three curves in Fig. 6, the c represents maximum yield stress, b indicates maximum normal stress, and a means maximum shear stress. In the initial period of the iterative calculation, pile stress is small, and the material was not fully used. With the increase of the iterative calculation times, the maximum yield stress and maximum stress promotes within its allowable areas. Fig. 7 reflects the fineness ratio can match with the requirements of the stability. The change of the displacement of the pile top is shown in Fig. 8, it reaches the maximum after 4 times iterative calculation, which exceeds the upper limit of the allowable displacement, and the latter calculation result will be very close to the allowable value. The results of the iterative calculation suggest that: after 7 times iterative calculation of mono-pile foundation, objective function can almost reach the optimal values, the optimal result of all the state variable are shown in table 3, among which the displacement of the pile top is the principal stressed condition. Because in the offshore wind generation, the pile foundation sustains the tower drum and principal part of the wind turbine nearly 70~120m high, tiny movement of the pile top will be magnified tenfold in the engine room. So as to ensure the wind turbine normally operates, the displacement of the pile top must be limited in a small range.

IV. CONCLUSION

Designing a secure, reasonable and economical foundation is the key problems of decreasing the cost of developing offshore wind power resources. This paper analyzed the pile size optimization of offshore wind turbine with mono-pile foundation optimization model, based on ANSYS zero-order method, and drew some conclusion as follows combining with the optimization results:

- 1) Provided the displacement, stress and stability is ensured, by optimizing the pile foundation of wind turbine, the thickness of the pile foundation reduced, and the objective function (the total volume of the pile foundation) decreased by 33.5%. The economic effect is optimistic, and the aim of the light-duty design is reached at the same time.
- 2) The displacement of pile top is the vital stressed condition in the optimization process, while designing the wind turbine. With the aim of sufficiently utilizing the strength of the material, the shape topology optimization of the foundation should be taken into consideration. Then, we can reduce the thickness of the pile in certain locations properly on the condition that the displacement of the pile top is ensured.

ACKNOWLEDGMENTS

The authors are thankful to the reviewers for the comments that helped to improve the clarity of the paper. The financial support by Chongqing Natural Science Foundation of China (Project Number: cstc2013jjB0003) and Higher Education Doctoral Fund Project (Project Number: 20125522110004) are gratefully acknowledged.

REFERENCES

- [1] G L Yoon, S B Kim, and H Y Kim, "Reliability analysis of mono-pile for offshore wind foundations using the response surface method," *New Frontiers in Geotechnical Engineering*, vol. 26, iss. 28, pp. 108-117, May 2014.
- [2] P Agarwal and L Manuel, "Reliability analysis and design procedures for offshore wind turbines," *Structures Congress*, vol. 24, iss. 26, pp. 1-9, Apr. 2008.
- [3] M Torcinaro, F Petrini, and S Arangio, "Structural offshore wind turbines optimization," *Earth and Space*, vol. 14, iss. 17, pp. 2130-2142, Mar. 2010.
- [4] F Bontempi, "Advanced topics in offshore wind turbines design," *Earth and Space*, vol. 14, iss. 17, pp. 1981-1991, Mar. 2010.
- [5] H G Kang, Y G Li, and C Y Huan, "RBDO method research of offshore wind turbine foundation structure," *Acta Energiæ Solaris Sinica*, vol. 30, iss. 12, pp. 1602-1607, Dec. 2009.
- [6] H G Kang, D M Sun, R J Mo, Y Ma, and W Li, "Structural optimization of grouted connection in offshore wind turbine foundations," *Journal of Shenyang Jianzhu University (Natural Science)*, vol. 29, iss. 1, pp. 77-85, Jan. 2013.
- [7] C Yang, "Integrated design and research of the pile foundation of offshore wind turbine," *Harbin: Harbin Engineering University*, Dec. 2008.
- [8] C Y Xuan, "Design and research of pile-style foundation structures for offshore wind turbine," *Dalian: Dalian Technology University*, Jun. 2009.
- [9] Y Yan, "Design of structure optimization with APDL," *Journal of East China Jiaotong University*, vol. 21, iss. 4, pp. 52-54, Aug. 2004.
- [10] T Guo, A Q Li, and H Wang, "Research in form-finding of suspension structures based on Newton-Raphson iteration and zero-order optimization arithmetic," *Engineering Mechanics*, vol. 24, iss. 4, pp. 142-146, Apr. 2007.
- [11] S P Liu, M Zhang, and Y S Duan, "Cable force calculation of Da-ning-he bridge based on zero-order optimization method," *Municipal Engineering Technology*, vol. 27, iss. 4, pp. 354-356, Jul. 2009.
- [12] H R Wu, X P Wang, D P Gou, and X X Li, "Optimization design of tower crane mast based on ANSYS zero-order method," *Design and Calculation*, vol. 45, iss. 2, pp. 42-46, Feb. 2014.