Zonal Coupling Analysis Method of Seismic Response of Offshore Monopile Wind Turbine

XU Xiaofeng[1,2], *CHEN Shaolin*[1*], *SUN Jie*[3]

1. College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, P. R. China;
2. East China Electric Power Design Institute Co., Ltd., China Power Engineering Consulting Group, Shanghai 200063, P. R. China; 3. Jiangsu Power Design Institute Co., Ltd., China Energy Engineering Group, Nanjing 211106, P. R. China

(Received 20 May 2024; revised 28 July 2024; accepted 5 August 2024)

Abstract: The seismic safety of offshore wind turbines is an important issue that needs to be solved urgently. Based on a unified computing framework, this paper develops a set of seawater-seabed-wind turbine zoning coupling analysis methods. A 5 MW wind turbine and a site analysis model are established, and a seismic wave is selected to analyze the changes in the seismic response of offshore monopile wind turbines under the change of seawater depth, seabed wave velocity and seismic wave incidence angle. The analysis results show that when the seawater increases to a certain depth, the seismic response of the wind turbine increases. The shear wave velocity of the seabed affects the bending moment and displacement at the bottom of the tower. When the angle of incidence increases, the vertical displacement and the acceleration of the top of the tower increase in varying degrees.

Key words: offshore monopile wind turbine; seismic response analysis; soil-junction interactions; fluid-structure inter-action

CLC number: TU31 **Document code:** A **Article ID:** 1005-1120(2024)S-0103-08

0 Introduction

Vigorously developing renewable energy is an important support for accelerating the construction of ecological civilization. Among them, wind energy has developed rapidly with its abundant reserves and high utilization rate[1]. Offshore wind turbines can capture richer and longer-lasting wind energy. However, in the maritime areas of China, earthquakes are frequent in the seas. Undersea earthquakes and their induced secondary disasters can cause devastating damage to offshore structures[2]. How to ensure the seismic safety of offshore wind turbines is an important issue facing the development of offshore wind turbines.

The seismic response analysis of offshore wind turbines is an important part of ensuring their seismic safety, and the coupling effect of seawater-seabed-wind turbine under earthquake action needs to be considered. As an input to the seismic response analysis of offshore wind turbines, the free-field response is the basis for studying seismic wave scattering. Thomson et al.[3] gave the transfer matrix solution of the wave propagation problem in the layered media, which is widely used in the reflection and transmission problem of plane waves, but mostly considered for dry soil. Moreover, the free field on the side and bottom boundary of the sea field is simplified: The effect of the free field is ignored by directly entering ground motion at the bottom[4]; Or consider only one of the bottom and side free fields[5-6].

The implementation of artificial boundaries can transform the infinite field fluctuation scattering problem into a finite field problem. At present, artificial boundaries include transmission boundaries, viscoelastic boundaries and viscoelastic boundaries,

*Corresponding author, E-mail address: iemcsl@nuaa.edu.cn.

How to cite this article: XU Xiaofeng, CHEN Shaolin, SUN Jie. Zonal coupling analysis method of seismic response of offshore monopile wind turbine[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2024, 41(S): 103-110.
http://dx.doi.org/10.16356/j.1005-1120.2024.S.013

and the most widely used one is viscoelastic boundaries[7-8]. However, the viscoelastic boundary is inconvenient to apply when the soil layer is saturated.

On this basis, the seawater-seabed-wind turbine interaction analysis needs to be considered[9-12]. First, there is a coupling of solid-liquid phases on the seabed itself, and secondly, there is a coupling between the seabed, the overlying seawater layer and the lower foundation of the wind turbine. Among them, the seawater-structure coupling belongs to fluid-structure interaction, which is mostly simplified to the Morison equation[13], the radiation wave theory[14] and the additional mass method[15]. Seabed-structure coupling belongs to soil-junction interaction, which is mostly simplified into the lumped parameter method, the substructure method and the overall analysis direct method, which is very inconvenient to solve. At present, most of the domestic and foreign only consider one or two of the three couplings of seawater-seabed, seabed-structure and seawater-structure, and it is one-way coupling and simplified.

Based on this, this paper intends to unify the seawater, saturated seabed and wind turbine foundation into generalized saturated porous medium, so as to achieve coupling, adopt centralized mass explicit finite element analysis for the site, the implicit finite element analysis for the structure, realize the time-step coupling through overlapping layer units between the explicit and implicit, and implement the efficient zoning analysis of seawater-saturated seabed-fan interaction combined with the transmission artificial boundary conditions.

1 Theory

The seawater-saturated seabed-wind turbine interaction analysis problem is essentially a seismic wave scattering problem. The specific solution process is a free field analysis and an implementation of artificial boundaries. Environmental media-structure interaction analysis is shown in Fig.1.

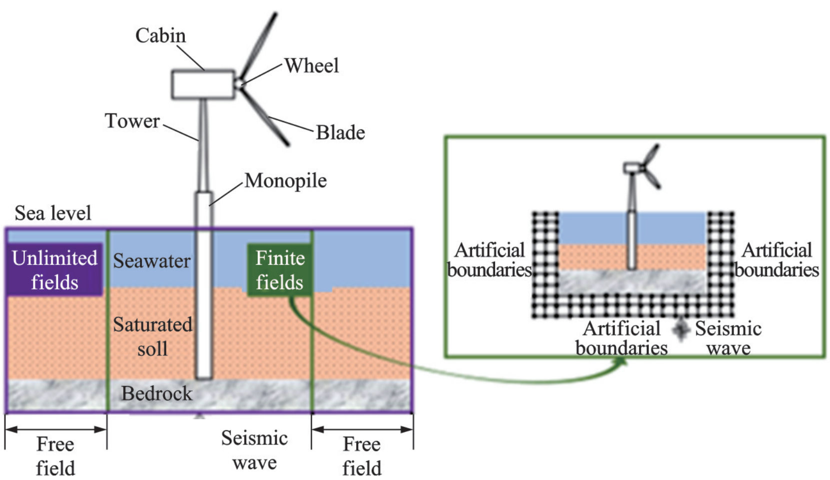


Fig.1 Schematic diagram of wind turbine seismic response analysis

1.1 Free field analysis

The free field response, which is the site response under seismic excitation when there is no structure, provides input to the wave scattering problem. The general assumption is horizontal layered half-space, which has less impact on the seismic response of the wind turbine structure of interest. According to the seismic motion of the control point at the known water-soil interface, the seismic excitation at the input of the half-space control point of bedrock is obtained by inversion using the transfer matrix method. After obtaining the incident wave at the bedrock input, the free field response of the transmission boundary zone can be obtained and shown as $\boldsymbol{u}_{\mathrm{f}}$ and $\boldsymbol{U}_{\mathrm{f}}$.

1.2 Site analysis in the sea area

Site analysis is divided into artificial boundary node area and internal node area: The former is calculated by the multiple transmission formula, and the latter is calculated according to the theory of generalized saturated porous media.

The solid and liquid phase displacement recursive formulas for the internal junction are as follows

$$\boldsymbol{u}_i^{(p+1)} = 2\boldsymbol{u}_i^p - \boldsymbol{u}_i^{(p-1)} - \frac{(\Delta t)^2}{m_i^{\mathrm{s}}}(\boldsymbol{F}_i^{sp} + \boldsymbol{T}_i^{sp} - \boldsymbol{S}_{\mathrm{Ni}}^{sp} - \boldsymbol{S}_{\mathrm{Ti}}^{sp}) \quad (1)$$

$$\boldsymbol{U}_i^{(p+1)} = 2\boldsymbol{U}_i^p - \boldsymbol{U}_i^{(p-1)} - \frac{(\Delta t)^2}{m_i^{\mathrm{w}}}(\boldsymbol{F}_i^{\mathrm{w}p} + \boldsymbol{T}_i^{\mathrm{w}p} - \boldsymbol{S}_{\mathrm{Ni}}^{\mathrm{w}p} - \boldsymbol{S}_{\mathrm{Ti}}^{\mathrm{w}p}) \quad (2)$$

where $\boldsymbol{u}_i$ and $\boldsymbol{U}_i$ are the solid and liquid phase displacements of the nodes; m_i^{s} and m_i^{w} the solid and liquid phase masses of the nodes, respectively; $\boldsymbol{F}_i^{\mathrm{s}}$ and $\boldsymbol{F}_i^{\mathrm{w}}$ the solid and liquid constitutive forces of the node, respectively; $\boldsymbol{T}_i^{\mathrm{s}}$ and $\boldsymbol{T}_i^{\mathrm{w}}$ the solid and liquid viscosity resistance of the node, respectively; superscripts $p-1$, p and $p+1$ the three adjacent moments of the node, respectively; $\boldsymbol{S}_{\mathrm{Ni}}^{sp}$ and $\boldsymbol{S}_{\mathrm{Ti}}^{sp}$ the interfacial normal force and the interface tangential force acting on the solid phase at the junction, respectively; and $\boldsymbol{S}_{\mathrm{Ni}}^{\mathrm{w}p}$ and $\boldsymbol{S}_{\mathrm{Ti}}^{\mathrm{w}p}$ the interfacial normal force and interfacial tangential force acting on the junction liquid phase at all time. Δt is the time step.

According to the interfacial continuity conditions, the interfacial force acting on the solid and liquid phases of the junction i at the time of p can be derived. According to the interface force, the displacement response of the interface point can be obtained.

The total displacement fields $\boldsymbol{u}$ and $\boldsymbol{U}$ of the boundary nodes are divided into scattering fields $\boldsymbol{u}_{\mathrm{s}}$, $\boldsymbol{U}_{\mathrm{s}}$ and free fields $\boldsymbol{u}_{\mathrm{f}}$, $\boldsymbol{U}_{\mathrm{f}}$ by wave field decomposition, that is

$$\boldsymbol{u} = \boldsymbol{u}_{\mathrm{s}} + \boldsymbol{u}_{\mathrm{f}} \quad (3)$$

$$\boldsymbol{U} = \boldsymbol{U}_{\mathrm{s}} + \boldsymbol{U}_{\mathrm{f}} \quad (4)$$

Among them, the free field displacements $\boldsymbol{u}_{\mathrm{f}}$ and $\boldsymbol{U}_{\mathrm{f}}$ can be obtained according to Section 1.1. Using the multiple transmission technique, the outward scattering of the layman wave is simulated, and the scattering field displacement of the boundary node i can be obtained as

$$\boldsymbol{u}_{i\mathrm{s}}^{(p+1)} = \sum_{k=1}^{N}(-1)^{k+1}C_k^N \boldsymbol{u}_{k\mathrm{s}}^{(p+1-k)} \quad (5)$$

$$\boldsymbol{U}_{i\mathrm{s}}^{(p+1)} = \sum_{k=1}^{N}(-1)^{k+1}C_k^N \boldsymbol{U}_{k\mathrm{s}}^{(p+1-k)} \quad (6)$$

where C_k^N is the binomial coefficient, which is

$$C_k^N = \frac{N!}{k!(N-k)!} \quad (7)$$

Node k is the point pointing in the normal direction at boundary node i towards the interior of the calculation area, and its scattering displacement can be obtained by Eqs.(3) and (4), which are the transmission order.

After obtaining the scattering field displacements $\boldsymbol{u}_{\mathrm{s}}$ and $\boldsymbol{U}_{\mathrm{s}}$ of the boundary point from Eqs.(5) and (6), the total displacements $\boldsymbol{u}$ and $\boldsymbol{U}$ of the boundary points can be obtained from Eqs. (3) and (4).

1.3 Wind turbine structure analysis

The offshore wind turbine structure is calculated using the Newmark implicit integral method. If the response of the $p+1$ time node of the boundary node of the wind turbine calculation area is obtained from the field calculation area of the sea area, the dynamic balance equation of the $p+1$ time in the calculation area is

$$\left(K + \frac{1}{\beta(\Delta t)^2}M + \frac{\gamma}{\beta\Delta t}C\right)\boldsymbol{u}^{p+1} = F^{p+1} + M\left(\frac{1}{\beta(\Delta t)^2}\boldsymbol{u}^p + \frac{1}{\beta\Delta t}\dot{\boldsymbol{u}}^p + \left(\frac{1}{2\beta}-1\right)\ddot{\boldsymbol{u}}^p\right) + C\left(\frac{\gamma}{\beta\Delta t}\boldsymbol{u}^p + \left(\frac{\gamma}{\beta}-1\right)\dot{\boldsymbol{u}}^p + \left(\frac{\gamma}{2\beta}-1\right)\Delta t\ddot{\boldsymbol{u}}^p\right) \quad (8)$$

where K is the stiffness, M the mass, C the damping, F the external force, $\dot{\boldsymbol{u}}$ the velocity, and $\ddot{\boldsymbol{u}}$ the acceleration. γ, β are the Newmark integral format parameters.

1.4 Coupling analysis

The seawater-saturated seabed-wind turbine coupling analysis is realized by the zonal parallel method, that is, seawater, seabed and wind turbine foundation are analyzed by centralizing mass explicit finite element as display areas. The superstructure of the wind turbine is analyzed by implicit finite elements as an implicit calculation area. The coupling analysis between the wind turbine superstructure and the sea site is achieved by setting up a layer of explicit and implicit overlapping elements.

2 Example Analysis

2.1 Model and ground motion input

Taking the northeast sea area of Jiangsu province as an example, the size of the calculation area is 40 m×40 m×70 m, of which the seawater layer thick is 20 m, the saturated seabed layer is 40 m, and the bedrock layer is 10 m. Select a fan with a rated power of 5 MW. The diameter of the wind wheel is 126 m, the hub height is 90 m, and the number of blades is 3. The fan foundation adopts a large-diameter monopile foundation, and the fan monopile penetrates 60 m deep into the soil layer and exposes 10 m above the water. The site and foundation medium parameters are shown in Table 1.

Table 1 Environmental media parameters

Material	Shear modulus/Pa	Poisson's ratio	Density/(kg•m^{-3})	Shear wave velocity/(m•s^{-1})
Seawater	—	0.05	1 000	0
Seabed	2.50E8	0.30	2 000	445
Bedrock	4.80E9	0.20	2 643	1 348
Monopile	8.08E10	0.30	7 850	3 208

ANSYS software is used to model with BEAM189 elements for the nacelle and tower, SHELL63 elements for the blades, and SOLID185 elements for the foundation. The site and foundation are modeled by self-programmed programs, using hexahedral solid elements. The unit size is 1 m×1 m×1 m, the perpendicularly polarized shear vertical (SV) wave is incident vertically, and the time step is 4×10^{-5} s, which meet the accuracy requirements of wave simulation. The wind airfield ground model is shown in Fig.2.

In order to consider the influence of three factors, seawater depth, seabed wave velocity and incidence angle on the seismic response of offshore wind turbines, 12 working conditions are designed through control variables, as shown in Table 2.

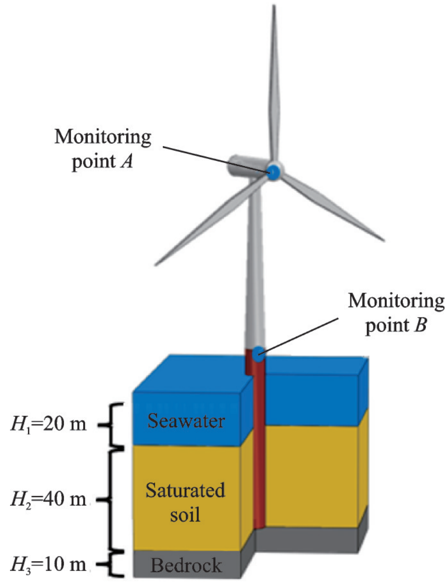


Fig.2 Schematic diagram of the wind turbine model site

Table 2 Working conditions of different cases

Case	Sea depth/m	Seabed wave speed/(m•s^{-1})	Angle of incidence/(°)
Case 1	10	445	0
Case 2	15	445	0
Case 3	20	445	0
Case 4	25	445	0
Case 5	20	445	0
Case 6	20	753	0
Case 7	20	953	0
Case 8	20	1 128	0
Case 9	20	445	0
Case 10	20	445	15
Case 11	20	445	25
Case 12	20	445	35

According to the results of seismic safety assessment in Rudong Sea, Jiangsu, the acceleration response spectrum of the target located on the surface of the seabed is obtained. According to the NGA-West ground motion database, a seismic wave consistent with the site characteristics is selected for time history analysis, and the seismic wave is inverted to the bottom of the bedrock. Seismic waves are incident perpendicularly as SV waves. Seismic waves are recorded by Corinth Station of the 1981 Corinth_Greece earthquake with a duration of 41.29 s. The seismic recording horizontal acceleration time history plot and spectrogram are shown in Fig.3.

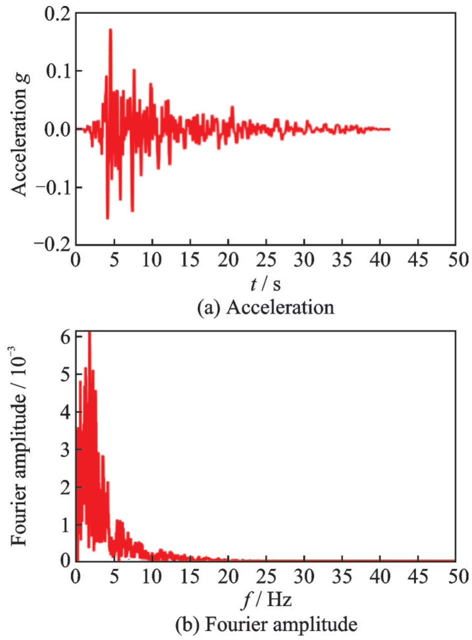


Fig.3 Horizontal acceleration time history plot and spectrogram

2.2 Result analysis

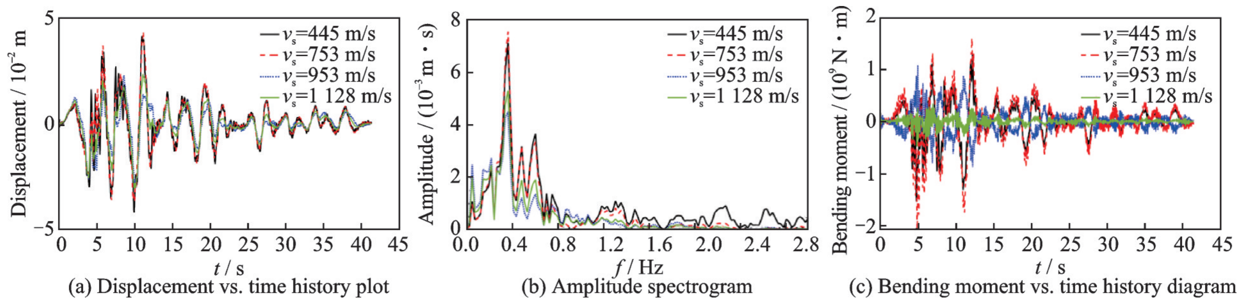
The changes of seawater depth H_w from 10 m to 15 m, 20 m, and 25 m are controlled, and the responses of monitoring points A and B (shown in Fig.2) are analyzed to explore the influence of seawater depth on the seismic response of offshore wind turbines.

Seismic response results under different water depth conditions are shown in Table 3. It can be seen from the results of Table 3 that the absolute displacement of the fan tower first decreases and then increases with the increase of water depth. The absolute velocity and bending moment peak of the fan tower increase or decrease slightly when the water depth changes from 10 m to 15 m, significantly increase at 20 m, and decrease sharply at 20 m to 25 m. The absolute acceleration peak of the top point of the tower changes with the bending moment of the water depth, but the acceleration peak of the top point of the tower does not change significantly when the water depths are 10 m, 15 m, and 20 m, while significantly smaller at 30 m. The displacement, velocity, acceleration and bending moment of the top and bottom points of the wind turbine tower peak at a sea depth of 20 m, which should be closer to the excellent frequency of seismic input at a water depth of 20 m.

The displacement response of monitoring point A and the bending moment response of monitoring point B at different seabed wave velocities v_s are shown in Fig.4. It can be found that with the increase of seabed shear wave velocity, the peak value of the displacement time history diagram first increases and then decreases, the maximum bending moment first increases and then decreases, and the bending moment time history graph has obvious high frequency, because the bending moment is related to acceleration and the acceleration signal is sensitive to high frequency. And as the wave speed slowly increases, the overturning bending moment at the bottom of the tower first increases slightly and then gradually decreases.

Table 3 Seismic responses result under different water depth conditions

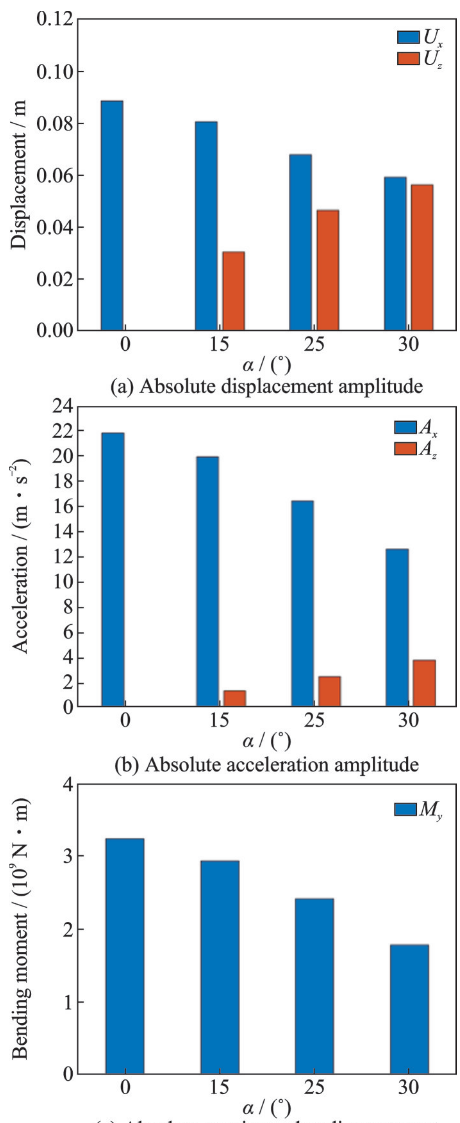
Monitoring point	H_w	Absolute displacement peak/m	Absolute speed peak/(m•s^{-1})	Absolute acceleration peak/(m•s^{-2})	Absolute maximum bending moment/(N•m)
A	H_w=10 m	0.069 0	0.537 9	12.466 7	2.773 5E8
	H_w=15 m	0.064 0	0.556 4	11.524 3	2.600 7E8
	H_w=20 m	0.082 0	0.834 8	19.210 7	4.101 8E8
	H_w=25 m	0.063 3	0.451 8	12.195 2	2.819 4E8
	Trend				
B	H_w=10 m	0.100 0	0.903 7	17.881 0	1.573 3E9
	H_w=15 m	0.090 8	0.936 5	17.267 2	1.376 9E9
	H_w=20 m	0.104 6	1.662 4	17.634 3	2.816 5E9
	H_w=25 m	0.099 5	0.737 9	13.872 4	1.443 5E9
	Trend				



(a) Displacement vs. time history plot (b) Amplitude spectrogram (c) Bending moment vs. time history diagram

Fig.4 Seismic response of wind turbine towers under different seabed wave velocity conditions

As the angle of incidence α changes, both the horizontal and vertical displacements change, as shown in Fig.5. It can be found that with the increase of the angle of incidence, the vertical displacement and acceleration response are getting bigger and bigger, the horizontal displacement and acceleration response are generally getting smaller and smaller, and the maximum bending moment is getting smaller and smaller. The above variation law occurs because as the incidence angle increases in the x-z plane, the x-direction component gradually decreases, and the z-direction component gradually increases. Therefore, the displacement and acceleration in the x-direction and the bending moment affected by the force in the x-direction decrease, while the acceleration in the z-direction increases.



(a) Absolute displacement amplitude

(b) Absolute acceleration amplitude

(c) Absolute maximum bending moment

Fig.5 Seismic recording of the seismic response of wind turbine towers at different angles

3 Conclusions

Based on the unified calculation framework of generalized saturated porous media, this paper proposes a set of efficient zoning analysis methods for seawater-seabed-offshore monopile wind turbine coupling. The methods comprehensively consider the soil-junction interaction effect and fluid-structure interaction effect. Moreover, this paper analyzes the seismic response of offshore monopile wind turbines on a site in a sea area in the East China Sea, and the effects of seawater depth, seabed wave velocity and incidence angle on the seismic response of offshore wind turbine towers. The following conclusions are drawn.

(1) The variation of seawater depth, on the one hand, changes the free field (seismic input) in the sea area, and on the other hand, changes the self-vibration characteristics of the overall system of the sea site-wind turbine, thereby affecting the reaction of the wind turbine structure. Therefore, seawater depth has a great influence on the seismic response of wind turbines. When the seawater increases to a certain depth (such as 20 m in the example in

this paper), the fan reacts the most when the self-resonance frequency of the overall system of the sea-site-wind turbine is close to the frequency of the input seismic wave.

(2) The influence mechanism of seafloor shear wave velocity on the seismic response of wind turbines is essentially the same as that of seawater depth, both of which change the free field and the self-vibration characteristics of the system. Relatively, the seabed shear wave velocity has a greater influence on the overturning moment of the wind turbine than the displacement at the top of the tower.

(3) With the increase of the incidence angle of seismic waves, the horizontal displacement, acceleration and overturning moment decrease in varying degrees, and the vertical displacement and acceleration increase in different degrees.

The example in this paper is only a linear case, and does not consider the nonlinearity of the seabed and the nonlinearity of the wind turbine structure. In the nonlinear situation, the influence of seawater depth, shear wave velocity, incidence angle and other factors on the fan response should be different, such as oblique incidence will increase the vertical acceleration of the tower top. If the second-order effect is considered, it will increase the horizontal reaction of the structure, which needs further study.

References

[1] WANG Jian, LI Xiang, HAN Xue, et al. Analysis of spatiotemporal distribution characteristics of offshore wind energy resources in China[J]. Marine Forecasts, 2022, 39(6): 55-61.

[2] LI Xiaojun, LI Na, CHEN Su. Study on seismic zoning in China sea area and its key issues[J]. Technology for Earthquake Disaster Prevention, 2021, 16(1): 1-10.

[3] THOMSON W T. Transmission of elastic waves through a stratified solid medium[J]. Journal of applied Physics, 1950, 21(2): 89-93.

[4] WANG Yanzheng, FAN Hongfei, ZHAO Kai, et al. 2D nonlinear seismic response characteristics of a strait site with deep inhomogeneous soil deposits[J/OL]. Chinese Journal of Geotechnical Engineering. DOI: 10.11779/CJGE20221307.

[5] WANG Yangyang, JING Yueling, ZHOU Zhaohu. Dynamic response analysis of power house at Dam Toe under obliquely incident waves[J]. Water Resources and Power, 2019, 37(5): 45-48.

[6] SONG Z, WANG F, LI Y, et al. Nonlinear seismic responses of the powerhouse of a hydropower station under near-fault plane P-wave oblique incidence[J]. Engineering Structures, 2019, 199: 109613.

[7] WANG Zhan, JING Liping, LU Xinyu, et al. Comparative study of viscous-spring boundary element and methods of seismic motion input[J]. World Earthquake Engineering, 2023, 39(2): 167-177.

[8] LIU Jingbo, BAO Xin, LI Shutao, et al. Stability conditions of explicit algorithms when using viscoelastic artificial boundaries[J]. Explosion and Shock Waves, 2022, 42(3): 034201.

[9] ZUO Haoran, BI Kaiming, HAO Hong. Dynamic analyses of operating offshore wind turbines including soil-structure interaction[J]. Engineering Structures, 2018, 157: 42-62.

[10] YANG Y, YE K, LI C, et al. Dynamic behavior of wind turbines influenced by aerodynamic damping and earthquake intensity[J]. Wind Energy, 2018, 21(5): 303-319.

[11] WANG P, ZHAO M, DU X, et al. Wind, wave and earthquake responses of offshore wind turbine on monopile foundation in clay[J]. Soil Dynamics and Earthquake Engineering, 2018, 113: 47-57.

[12] HE R, KAYNIA A M, ZHANG J, et al. Seismic response of monopiles to vertical excitation in offshore engineering[J]. Ocean Engineering, 2020, 216: 108120.

[13] WEI Kai, YUAN Wancheng. A numerical-analytical mixed method of hydrodynamic effect for deep-water elevated pile cap foundation under earthquake[J]. Journal of Tongji University: Natural Science, 2013(3): 336-341.

[14] WESTERGAARD H M. Water pressure on dams during earthquakes[J]. Transcations of the American Society of Civil Engineers, 1933, 98: 418-433.

[15] LIAW C Y, CHOPRA A K. Dynamics of towers surrounded by water[J]. Earthquake Engineering and Structural Dynamics, 1974, 3: 33-49.

Acknowledgements This work was supported in part by the National Natural Science Foundation of China (Nos. 51978337, U2039209).

Authors Ms. **XU Xiaofeng**, as a master's student in Nanjing University of Aeronautics and Astronautics (NUAA), is mainly engaged in the research of soil-structure interaction and seismic resistance of offshore structures.

Prof. **CHEN Shaolin**, as a professor and doctoral supervisor in NUAA, is mainly engaged in seismic response analysis and safety assessment of major engineering structures (nuclear power, dams, bridges, etc.), marine earthquake engineering and seismic metamaterials and their seismic isolation and absorption applications.

Author contributions Ms. **XU Xiaofeng** completed the modeling and seismic response analysis of the monopile wind turbine and wrote the manuscript. Prof. **CHEN Shaolin** provided guidance for data analysis and explored the change law of monopile wind turbines under the action of earthquakes. Mr. **SUN Jie** provided guidance for wind turbine modeling and site simulation in this paper. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: ZHANG Huangqun)

近海单桩式风机地震响应分区耦合分析方法

徐小凤[1,2]，陈少林[1]，孙 杰[3]

(1.南京航空航天大学民航学院，南京 211106，中国；2.中国电力工程顾问集团华东电力设计院有限公司，上海 200063，中国；3.中国能源建设集团江苏省电力设计院有限公司，南京 211106，中国)

摘要：海上风机的地震安全性问题是急需解决的重要课题。本文基于统一计算框架，发展了一套海水-海床-风机分区耦合分析方法，并建立了5 MW风机及场地分析模型，同时选取了一条地震波，分析了在海水深度、海床波速和地震波入射角度改变的情况下近海单桩式风机地震响应的变化。分析结果表明，当海水增加到某深度时，风机的地震响应会增大；海床剪切波速会影响塔底弯矩和位移；当入射角度增大时，塔顶竖向位移和加速度均有不同程度的增大。

关键词：近海单桩式风机；地震响应分析；土-结相互作用；流固耦合