Finite Element Time-History Analysis of Offshore Substation Considering Pile-Soil Interaction

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Abstract. As the key structure of offshore wind farm, offshore substation must ensure the safety of structure under earthquake. According to previous studies, the influence of pile-soil interaction on the dynamic response analysis of offshore platform structure under earthquake is particularly significant. In this study, an offshore substation located in a high seismic intensity area in China is taken as the research object, a refined FEM model considering pile-soil interaction is established based on the method of API Recommendation, and the structural safety under earthquake action is checked. The results show that the offshore substation structure meets the requirements of seismic fortification, and the structure is obviously affected by vertical earthquake.

Keywords: offshore substation; p-y curve; seismic performance; FEM; time-history analysis

1 Introduction

Offshore wind power is one of the most promising renewable energy resources. It has developed rapidly in China recent years. The offshore substation is the core of the offshore wind farm. It can connect dozens of offshore wind turbines and integrate the functions of gathering, boosting and transmission to complete the important task of outputting power to the land. Research on the seismic performance of the offshore substation is very important. At present, offshore substation is mainly constructed as fixed jacket steel platform structure. The functional requirements and structural importance of the offshore substation structure are quite high. Especially affected by the geological conditions of China's coastal sites, most of the offshore wind farm sites are located in high seismic intensity areas, and the structural safety of offshore substation under earthquake should be guaranteed. Therefore, research on the seismic performance has become an extremely urgent topic at this stage.

In the seismic analysis of offshore substation, the nonlinear interaction between pile and soil will change the dynamic characteristics and response of the structural system

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[1,2], which is particularly important for the nonlinear dynamic time-history response analysis. In this paper, based on a real offshore substation project located in a high seismic intensity area in Jiangsu China, a finite element model considering the pile-soil interaction by the calculation model from the recommendations of American Petroleum Institute [3-5] and Det Norske Veritas [6,7] is established. The seismic analysis of the structure under the action of moderate earthquake is conducted to clarify the dynamic response characteristics of the offshore substation structure and to check the structural safety.

2 Finite Element Modeling of the Offshore Substation

2.1 Introduction of the Substation Project

The offshore substation is composed of the upper platform structure and the lower jacket foundation. The platform structure has three stories, the axial size is 24.6 m×32.7 m, and the height is about 16 m. The elevation difference between the upper and lower horizontal braces of the jacket foundation is 17.4 m. The pile foundation uses four steel pipe piles with a diameter of 2.2 m. The pile length is about 99 m, the depth of pile tip is about 79.5 m, the elevation of the sea bed is -8.9 m, and the elevation of pile bottom is -88.0 m.

The structural design service life of the offshore substation is 50 years, and the seismic fortification intensity is 8 degrees. According to the seismic safety assessment report of the project site, the horizontal peak ground acceleration of moderate earthquake is 0.282 g and the characteristic period of the ground acceleration response spectrum is 0.65 s.

2.2 Modeling of the Offshore Substation and Pile-Soil Interaction

In this paper, the general finite element analysis software Abaqus is used to build the model. The FEM model of the offshore substation is shown in Fig. 1. The model is divided into three parts: platform structure, jacket foundation and pile. The long side direction of the platform structure is defined as X axis, the short side direction is Y axis, and the vertical direction is Z axis. When modeling the platform structure, only the main components of the frame structure such as beams and columns are considered, the platform floor is simulated by equivalent stiffness, and the non-structure members such as the profiled steel deck walls and the power equipment are not fine modeled. The structural members are simulated by B31 beam element, and the three structural parts are fixedly connected by Tie connectors. The whole model material is composed of DH36, Q355C and Q235B steel. The hydrodynamic pressure is applied to the jacket foundation in the water by Morison formula [8,9]. The structural damping of the model adopts Rayleigh damping, and the damping ratio of the whole structure is calculated as 5% specified by the API recommendation [5].

The simulation of pile-soil interaction is based on the calculation model from the API recommendations [3-5]. The *p-y* curve, *t-z* curve and *Q-z* curve of the soil are transformed into nonlinear springs on the pile nodes of the model. The nonlinear spring is established by the grounding spring element (Spring1) in Abaqus. The *p-y* springs are set in the *X*-axis and *Y*-axis directions, the *t-z* spring is set in the *Z*-axis direction of each node of the piles under the sea bed surface. The Springs are set every 0.5 m in elevation. The *Q-z* springs are set at four pile bottoms. The specific nonlinear spring arrangement is shown in Fig. 2. There are 1264 *p-y* springs, 632 *t-z* springs and 4 *Q-z* springs are set.

Table 1 shows the main soil parameters of the project site obtained from the field geological survey. The site is composed of several layers of sand and soft clay, and the sand layer accounts for the majority in the range of pile foundation.

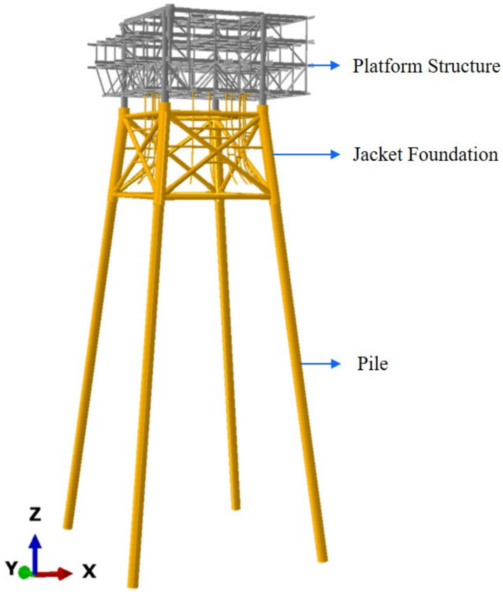

Figure 1. FEM model of the offshore substation

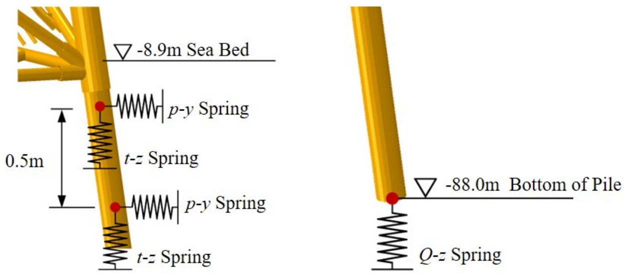

Figure 2. Calculation model of pile-soil interaction

3 Time-History Analysis of the Offshore Substation under Moderate Earthquake

3.1 Seismic Motion Input

In order to simulate the dynamic response of the offshore substation under moderate earthquakes in this site, three sets of natural seismic waves shown in Table 2 are selected from PEER NGA-West databases for time-history analysis according to the target seismic response spectrum. The horizontal acceleration of the seismic waves are amplificated to 0.282 g. According to the seismic design code [10], the ratio of the three axis's peak accelerations are set as X:Y:Z=1:1:2/3. Fig. 3 shows the horizontal acceleration response spectra of the selected earthquake waves. The seismic acceleration response spectra of three earthquake waves envelope the target response spectrum of the site well, which meets the requirements of covering the basic period range of the construction site.

Table 1. Mechanical properties and parameters of soil

Layer	**Soil Property**	**Layer Thickness** (m)	**Natural Unit Weight** (kN/m^3)	**Internal Friction Angle** (°)	**Undrained Shear Strength** (kPa)
1-1	sand	2.15	18.0	28	
1-2	sand	7.45	19.5	31	
1-3	sand	1.15	18.5	29	
2-1	soft clay	3.90	18.0		25.0
2-2	sand	4.49	18.5	27	
3-1	soft clay	8.51	17.5		25.0
3-2	soft clay	7.00	18.0		30.0
4-1	soft clay	6.00	18.5		45.0
4-2	sand	3.00	19.5	29	
5-1	sand	8.00	19.5	31	
6-1	sand	13.35	20.0	33	
6-2	sand	14.10	20.5	35	

Table 2. Details of the selected earthquake waves

No.	**RSN**	**Earthquake Name**	**Year**	**Magnitude**
EQ1	169	Imperial Valley	1979	6.53
EQ2	721	Superstition Hills	1987	6.54
EQ3	5975	El Mayor	2010	7.2

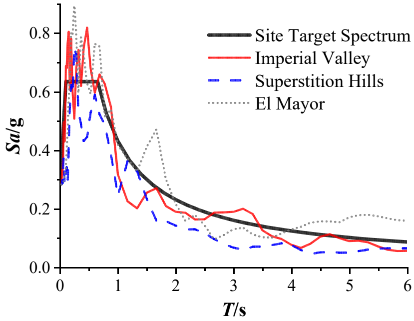

Figure 3. Comparison of three seismic acceleration response spectra and site target spectrum

3.2 Earthquake Response Analysis Results

This section analyzes the seismic performance of the offshore substation under three sets of seismic waves from three indicators: acceleration response, displacement response and stress response.

Acceleration Response. Fig. 4 shows the acceleration time-history curve of the jacket top under Imperial Valley wave. Table 3 summarizes the peak acceleration response at the top of the jacket under all three conditions. This paper defines the ratio of the peak acceleration response to the input peak acceleration as the acceleration amplification factor. In all cases, the vertical acceleration amplification factor is significantly greater than the horizontal factor. It can be seen that the heavy top platform structure of the offshore substation makes it different from the usual seismic response. So vertical seismic motion has a significant impact on the dynamic response of offshore substations and it should be considered during seismic design procedure.

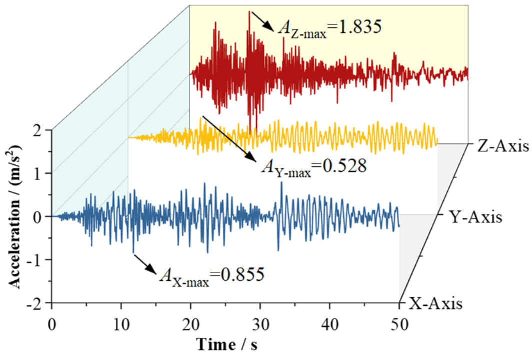

Figure 4. Acceleration time-history of the jacket top (EQ1)

Table 3. Peak acceleration response and amplification factor

No.	Direction	Peak Acceleration Response (m/s^2)	Acceleration Amplification Factor
EQ1	*X*	0.855	0.309
	Y	0.528	0.191
	Z	**1.835**	**0.996**
EQ2	*X*	1.050	0.380
	Y	0.754	0.273
	Z	**1.336**	**0.725**
EQ3	*X*	1.022	0.370
	Y	0.846	0.306
	Z	**1.637**	**0.889**

Comparing the horizontal acceleration response of *X* direction and *Y* direction under these cases, it can be seen that the response of *X* direction is larger than that of *Y* direction so that *X* direction plays a decisive role in the horizontal direction in the offshore substation structure. The reason is that there is a relatively large area of cantilever structure outside the four main columns connected to the foundation in the *X* direction of the platform structure, and the mass is larger than that in the *Y* direction. The overall stiffness of the platform structure in *X* direction is less than that in *Y* direction, which is easy to cause greater structural dynamic response.

Displacement Response.

Pile Displacement at the Sea Bed Surfacce. When designing the pile foundation of offshore substation, it is necessary to control the horizontal displacement of pile. The horizontal displacement of the pile foundation at the sea bed surface is generally used as the design indicators, and the peak value should be controlled under 1/10 of the pile diameter. In this wind farm project, the pile foundation of offshore substation uses Φ2200 steel pipe piles, so the peak horizontal displacement at the sea bed surface should be less than 220 mm.

Table 4 summarizes the peak horizontal displacement response of the pile foundation at the sea bed surface under all three analysis cases. It can be seen that the peak horizontal displacement of pile foundation is far less than the design requirement. The peak displacement response under each case is less than 5% of the allowable value.

Story Drift. Usually, the inter-story displacement is used to evaluate the deformation of the offshore substation under earthquake motion. The inter-story displacement of the structure should less than 1/250 of the story height to meet the seismic design requirements. This part selects the inter-story displacement between the upper and lower cross braces of the jacket foundation and the displacement between first and second story of the platform structure.

From Table 5 and Table 6, it can be seen that all of the inter-story displacements under the three cases meet the design requirement. The peak inter-story displacement response of the jacket foundation is less than 40% and the response of the platform structure is less than 65% of the allowable value.

Table 4. Pile displacement response at the sea bed surface

No.	Pile Displacement at the sea bed surface (mm)	Allowable Value (mm)	Ratio (%)
EQ1	5.2	220	2.36
EQ2	8.0		3.64
EQ3	10.5		4.77

Table 5. Inter-story displacement of jacket foundation

No.	Inter-story Displacement of Jacket Foundation (mm)	Allowable Value (mm)	Ratio (%)
EQ1	12.5	84.0	14.88
EQ2	19.6		23.33
EQ3	32.2		38.33

Table 6. Inter-story displacement of first-to-second story

No.	Inter-story Displacement of First-to-second Story (mm)	Allowable Value (mm)	Ratio (%)
EQ1	5.8	20.0	29.00
EQ2	6.9		34.50
EQ3	12.8		64.00

Stress Response. Due to the large number of electrical equipment which is the core functional component installed in the platform structure of the offshore substation, the structural safety is very important to ensure the stability of the entire offshore wind farm. Therefore, it is necessary to check the stress response of the structural members of platform structure.

Fig.5 shows the stress distribution contour of the platform structure of the offshore substation under Imperial Valley waves. It can be seen from the figure that the maximum stress of the platform structure appears at the H-shaped steel secondary beam where the main 220 kV transformer is located on the first story. In other cases, the peak stress also appears at this position. From the overall stress distribution, it can be seen that the stress response is relatively large near the four main steel pipe columns which connected the platform structure to the jacket foundation. It is also quite large on the locations of the large mass power equipment. The peak stress just appears at the location of the heaviest equipment in the offshore substation. It can be seen that during the seismic design of the platform structure, these positions need to be mainly considered.

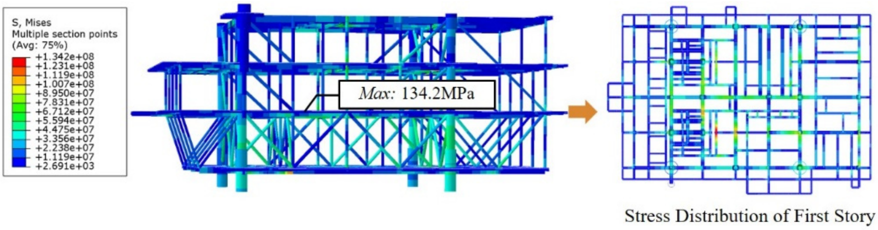

Figure 5. Mises stress distribution of platform structure (EQ1)

Table 7 summarizes the max Mises stress response of the platform structure members under all three analysis cases. It can be seen that the max stress is lower than the allowable stress. The max stress is 160.88 MPa under Superstition Hills waves, which is about 78% of the allowable stress of the Q355C steel.

Table 7. Max stress response of the plaatform structure

No.	**Max Stress** (MPa)	**Allowable Value** (MPa)	**Ratio** (%)
EQ1	134.20		64.83
EQ2	160.88	207.00	77.72
EQ3	141.96		68.58

4 Conclusions

In this paper, seismic time-history analysis based on finite element method is conducted on a real offshore substation structure considering the pile-soil interaction by the calculation model from the API recommendations. The conclusions are as follows:

1) The offshore substation structure meets the seismic fortification requirements of the current seismic design codes on displacement and stress under medium earthquakes.

2) According to the seismic time-history analysis results, the amplification factor of the vertical acceleration response of the offshore substation is obviously larger than that of the horizontal acceleration response. Therefore, the influence of vertical seismic motion must be considered in the seismic design of offshore substation.

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