Seismic response and spectrum analysis of offshore wind farm sites in Jiangsu Province, China

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Abstract. Presently, the offshore wind farms in Jiangsu Province account for 70%–75% of the total installed capacity in China. However, this is a geologically active earthquake area. In this study, we propose a typical site model based on the detailed survey data of an offshore wind farm in Dongtai, Jiangsu Province. Three ground motions (EL Centro, Northridge, and Kobe) were used as model inputs, and the propagation characteristics of an earthquake motion along an elevation were mainly studied. These include acceleration amplification effects, ground motion attenuation effects caused by liquefaction, site filtering effects, and long-period effects of the response spectrum. The results in time domain are as follows: (1) the site shows a nonlinear amplification effect along the elevation under different ground motions, but the amplification laws are different, which may depend on the spectrum components of the input ground motions; (2) along the elevation, the acceleration at the interface of deep clay and surface sand slightly decreased; (3) the ground motion cannot propagate in the time domain when surface soil reached a complete liquefaction state.

In the frequency domain: (1) during propagation, the high-frequency components are filtered quickly, and the attenuation of the components in the clay is weaker than that in the sand; (2) the dominant frequency of the input ground motion increases slightly (1~1.5 Hz) at depths of approximately 40~30 m, after which the dominant frequency of the ground motion decreases again (0.2~0.5 Hz); (3) the response spectrum gradually transits from single-peak short-period to double-peak long-period (approximately 3 s). The abovementioned site dynamic analysis can provide the basis for seismic research of offshore engineering sites, such as guiding the seismic design.
of offshore wind turbine foundations.

**Key words:** Offshore wind farm; Jiangsu offshore; Seismic response; Amplification effect; Spectrum analysis.

1. Introduction

Offshore wind turbine structures are highly susceptible to seismic response [1-2]. The dominant seismic frequency may overlap with the wind turbine's frequency domain, resulting in the strong vibration of the wind turbine [3-5]. The large-diameter piles are widely used for offshore wind turbine foundations, such that the dynamic behavior of the soils around the piles during earthquakes will affect the dynamic characteristics of the wind turbine [6]. Moreover, different offshore engineering sites have different responses to ground motions. For instance, the liquefiable sites will cause soil liquefaction, ground motion magnification, leading to intense vibration of offshore wind turbines [7]. For example, many offshore wind farms are distributed in Jiangsu Sea Area in China [8], where the coastal strata in Jiangsu are mostly loose silt and silt sand, which is at a high risk of soil liquefaction. And the liquefaction of the site will have a catastrophic impact on offshore wind farms.

Seismic activity is frequent in the regions around the Yellow Sea, with several potential seismogenic faults around offshore wind farms. The authors conducted a survey and collected design data from many offshore wind farms in this area. The positional relationship between offshore wind farms and fault zones is exhibited in Figure 1a, suggesting that offshore wind farms in the south Yellow Sea area are earthquake-prone with many historical seismic records (see Figure 1b). The North-Jiangsu Coastal Fault is located outside the coastal zone, extending intermittently toward the northwest at more than 200 kilometers. The fault has apparent activity (bad faulting) in the Quaternary, with significant impacts on the formation and development of modern coastlines. Seven destructive earthquakes have been recorded with six of them showing maximum magnitudes in the near-field area.

We selected a 200 MW offshore wind farm in Dongtai, Jiangsu Province, as the subject for case study.
The drilling data of 50 wind farm stations were analyzed. In addition, to ensure better model representation, the engineering geological survey data of an offshore wind farm in Dafeng on the north of Dongtai was referenced for the stratum modeling. The locations of the two offshore wind farms are shown in Figure 1, where the North-Jiangsu Coastal Fault passes through the offshore wind farms. The marine sites under different seismic design levels, including the dynamic response and the characteristics of frequency spectrum evolution of the wind farm, were studied using a one-dimensional (1D) seismic analysis program. The results can provide a basis for the pile foundation seismic optimization design of offshore wind turbines.

2. Site model for dynamic analysis

2.1. Ground motion

Three ground motions were used to analyze the site seismic response, EL Centro wave, Northridge wave, Kobe wave (abbreviated as EL, NR, and KB, respectively). The specific earthquakes records used are El Centro Array #4 (1979), Northridge-LA Dam station (1994), Kobe-Takatori station (1995). Figure 2 shows the time history and spectrum of the ground motions at peak ground acceleration (PGA) of 1 m/s².

The model is the 80 m site stratum established by typical boreholes. The three ground motions mentioned above are horizontally input from the bottom of the model. For all ground motions, the PGAs near the ground surface were multi-iterated to 0.05g, 0.1g, 0.2g, and 0.4g, respectively. The time interval of the three seismic records and the time interval of the numerical computation during the seismic action are 0.001 and 0.01 s, respectively. In addition, the time interval after the earthquake for pore pressure dissipation dynamically changed from 0.01 to 5 s.

![Image of Figure 2](image-url)

**Figure 2.** Time history and frequency spectrum of input ground motions

2.2. Strata parameters

The free-rotating drilling of the XY-II drilling rig was used for offshore drilling operations during the
survey. The exploration depth is the Quaternary sedimentary strata, covering many soil types: sand, silt, and cohesive soils. The drilling depth of this survey is 65.60–79.75 m, penetrating the silty sand layer (6)-1 into the silty sand layer (8) by more than 10 m. For easier investigation, similar strata were combined during the dynamic analysis. Consequently, six layers of site stratum, where the 1st, 2nd, 4th, and 6th stratum layers are simplified as liquefiable layers, and the 3rd and 5th layers denote nonliquefiable silty clays are observed (Table 1).

In the 1D seismic analysis program for the liquefiable sites, the liquefiable soil is described using a dynamic cyclic elastoplastic constitutive model (the E-P model). The nonliquefiable soil (3rd and 5th layers) is described using the Ramberg–Osgood constitutive model (R–O model) based on the viscoelastic theory [10]. Details on the constitutive model and related parameters were obtained from the literature [11-12].

The strata analyses are shown in Table 1, where the dynamic parameters are calibrated using triaxial and resonance column tests. Since the soil samples are primarily slightly disturbed silt sands, the remolded soil was used. The sine wave was applied with a 1-Hz frequency and a consolidation ratio, $k_c = 1.0$ in the dynamic triaxial test, using a pore pressure ratio, $r_u = 1$ as the liquefied criterion.

### Table 1. Simplified stratum dynamic analysis parameters of an offshore wind farm

| Parameters                              | 1st layer | 2nd layer | 3rd layer | 4th layer | 5th layer | 6th layer |
|-----------------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Initial void ratio (e0)                 | 0.728     | 0.67      | 0.98      | 0.75      | 0.94      | 0.64      |
| Permeability coefficient (m/s)          | 3.00E-06  | 6.00E-06  | 3.80E-10  | 5.00E-06  | 1.80E-09  | 1.00E-05  |
| Natural density (g/cm$^3$)              | 1.96      | 1.97      | 1.9       | 1.95      | 1.9       | 1.98      |
| Constitutive model                      | E-P       | E-P       | R-O       | E-P       | R-O       | E-P       |
| Compression index A                     | 0.011     | 0.01      | /         | 0.01      | /         | 0.01      |
| Rebound index k                         | 0.001     | 0.001     | /         | 0.001     | /         | 0.001     |
| Shear modulus ratio G0/σ$\nu$           | 1100      | 800       | /         | 600       | /         | 600       |
| Transformation stress ratio Mm          | 0.95      | 0.95      | /         | 0.95      | /         | 0.95      |
| Failure stress ratio MF                 | 1.25      | 1.25      | /         | 1.25      | /         | 1.25      |
| Hardening parameters B0                 | 2000      | 3500      | /         | 2800      | /         | 3000      |
| B1                                      | 30        | 30        | /         | 30        | /         | 30        |
| Cf                                      | 0         | 0         | /         | 0         | /         | 0         |
| Anisotropy parameter Cd                 | 2000      | 2000      | /         | 2000      | /         | 2000      |
| Expansion parameter D0                  | 1.3       | 1         | /         | 1         | /         | 1         |
| n                                       | 5         | 6         | /         | 4         | /         | 6         |
| Reference strain parameter $\gamma_{ref}$ | 0.005     | 0.005     | /         | 0.005     | /         | 0.005     |
| $\gamma_{ref}$                         | 0.1       | 0.1       | /         | 0.1       | /         | 0.1       |
| Poisson's ratio $\nu$                   | /         | /         | 0.38      | /         | 0.35      | /         |
| Cohesion c(KPa)                         | /         | /         | 40        | /         | 30        | /         |
| Internal friction angle (deg)           | /         | /         | 15        | /         | 20        | /         |
| Nonlinear coefficient $\alpha$          | /         | /         | 3         | /         | 3         | /         |
| Nonlinear coefficient $\beta$           | /         | /         | 2.3       | /         | 2.3       | /         |
| Shear modulus coefficient a             | /         | /         | 700       | /         | 740       | /         |
| Shear modulus coefficient b             | /         | /         | 0.55      | /         | 0.6       | /         |

### 3. Site dynamic analysis

#### 3.1. Analysis for peak amplifier and spectrum

The different ground motions in Figure 2 were used as inputs for the stratum model described in Table 2. As the seismic design of the site considers ground motions, all input ground motions are iterated to 0.05g, 0.1g, 0.2g, 0.4g at the ground surface. In addition, magnification effect and frequency evolution characteristics along the elevation were investigated.

Figure 3 shows the result of the EL wave at PGA = 0.05 g. The input ground motion at 80 m below the mud surface is shown in red, suggesting that the high-frequency components are gradually filtered along the elevation. A bimodal distribution was observed at 0.47 and 1.42 Hz ground motion frequencies between 48 and 36 m below the mud surface, respectively. Moreover, between 22 and 12 m below the mud surface, a single-peak frequency was observed, concentrated in 0.45–0.46 Hz, and few other frequency-domain components. Owing to the acceleration amplification effect near the ground surface, the grid nodes vibrate intensely, with high-frequency components of 2–3 Hz observed.
during the vibration.

Figure 4 shows the result of the EL wave at PGA = 0.2 g. Here liquefaction occurred around the ground surface, and the value of the excess pore pressure ratio was 1.0 in the strata of 0–12 m. No ground motion was recorded after 10 s at 2 m below the mud surface because the soil layer has reached a completely liquefied state. As shown in Figure 4, as the input PGA increased, the energy of each frequency also increased, but with low filtering of the high-frequency components. The frequency components are complex from 48 to 36 m below the mud surface, concentrated in 0~4 Hz. At 12~22 m below the mud surface, the frequency presents a single peak, concentrated in the range of 0.38~0.5 Hz, with few ground motion components of other frequency-domain components. Owing to the site liquefaction near the ground surface, the domain frequency of ground motion decreased to 0.3 Hz.

Figure 5 shows the results of the KB wave at PGA = 0.2 g, where soil liquefaction occurred near the ground surface. The primary frequency of the input ground motion gradually changed from 0.8~1.2 to 0.43~0.49 Hz near the surface. The frequency evolutionary characteristics are similar to the EL wave. However, the attenuation of the ground motion in the deep clay is weaker than that in the shallow sand, which can be owing to the liquefaction of the silty sand.

Figure 3. Acceleration and Fourier amplitude of El wave at
PGA = 0.05 g

The comparison of the amplification factors of different ground motions is shown in Figure 6. The time-domain analysis results showed that the site signifies a nonlinear magnification effect along the
elevation under different ground motions. The acceleration at the interface between the deep clay and the surface sand decreased slightly. Three ground motions exhibited the same phenomenon under different PGAs. In the deep layer, from 80 to 36 m, the acceleration amplification factor is 1.0–2.0. A complex relationship exists between the amplification factor and PGA. The acceleration amplification factor can be greater than 4.0 around the surface. When the seismic design intensity is VIII, the acceleration amplification factors of the ground surface are 2.28 (EL), 1.28 (NR), and 4.23 (KB), respectively.

3.2. Response spectrum evolution analysis

The response spectrum evolution of EL waves is shown in Figure 7, suggesting that the seismic response spectrum of the site gradually transitioned from a single-peak short period (0.25s) to a double-peak long period. When the input PGAs are 0.05g, 0.1g, 0.2g, and 0.4g the long-period derivative components are 2.12, 2.78, 2.98, and 3.14 s, respectively. Figure 7 shows that the ground motions gradually changed some frequency components similar to the site's dominant period (2–3s). This is because the site's dominant period was estimated on the basis of the relation between sediment thickness and predominant frequency by Guo et al. [13] and can also be verified by \( T = 4H/V_s \), where the 80-m thickness model has a measured shear wave velocity of approximately 160 m/s (20 m depth of surface layer).
Figure 4. Acceleration and Fourier amplitude of EI wave at PGA = 0.2g

Figure 5. Acceleration and Fourier amplitude of KB wave at PGA = 0.2g
Furthermore, owing to site liquefaction near the ground surface, the response spectrum period was extended. Combining these reasons, the response spectrum can be approximately 3.0 s, which is close to the natural frequency of the wind turbine structure. Once the earthquake occurs, the resonance between the site and wind turbine system will cause significant risks. Therefore, the dynamic site analysis above can guide offshore engineering design, such as assisting in the seismic design of offshore wind turbine foundations.

**Figure 6.** Comparison of amplification factors of different ground motions

4. Conclusions

This study investigated the seismic response of a liquefiable site of an offshore wind farm in the South Yellow Sea. The main conclusions are as follows:
(1) The high-frequency components of the ground motion were gradually filtered along the elevation—the wave frequencies (0.47 and 1.42 Hz) present double peaks at the deep and middle stratum. At shallow strata, the wave frequency presents a single peak, concentrated around 0.45–0.46 Hz.

(2) The site presents a nonlinear amplification effect along the elevation. Acceleration at the interface between the deep clay and the surface sand decreases slightly. In the deep layer, from 80 to 36 m, the acceleration amplification factor is 1.0–2.0; but near the surface, the acceleration amplification factor can be greater than 4.0.

(3) The response spectrum gradually evolved from a single-peak short period (0.25 s) to a double-peak long period. In addition, the liquefaction of the ground surface further extended the period of the response spectrum and can cause the response spectrum to vibrate at the natural frequency of the wind turbine structure.

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