Seismic Performance Analysis of Offshore Wind Jacket Substructure by Soil Modeling Method

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Abstract—Offshore wind turbines are accelerating the development of excellent sizes with various advantages, such as greater economic efficiency and scalability than terrestrial wind turbines. The most representative example is the application of monopile and jacket foundation for offshore wind turbine support. However, the monopile substructure is limited due to the limitation of equipment.

Fixed, Lumped, and Winkler models are applied to the integrated load analysis of offshore wind turbines.

In this study, the behavior of the offshore wind turbine jacket supporting structure according to the soil modeling method is examined. The target sea area is the site of Southwest Sea model complex site which is promoted by the government of Korea. Interpretation is performed by analysis response spectrum and time history. The above three models were applied to the soil(Fig 1, Table 1), and the top generator was applied to 5MW offshore wind turbine.

Keywords—Jacket substructure, Offshore wind turbine, Response spectrum, Time history, Seismic analysis, Soil modeling

I. INTRODUCTION

Offshore wind turbines are accelerating the development of excellent sizes with various advantages, such as greater economic efficiency and scalability than terrestrial wind turbines. The most representative example is the application of monopile and jacket foundation for offshore wind turbine support. However, the monopile substructure is limited due to the limitation of equipment.

In the case of general structure, the pile design is conservatively approaching the design by applying the fixed boundary to the soil without considering the ductility of the foundation. However, in the case of offshore wind turbine jacket substructure where horizontal load is dominant, design through integrated analysis of soil-structure-external load condition is essential.

Fixed, Lumped, and Winkler models are applied to the integrated load analysis of offshore wind turbines.

- **Fixed model**: apply soil as a rigid body
- **Lumped model**: apply soil as a k-matrix
- **Winkler model**: model a pile foundation and apply a rigidity spring to each depth

In this study, the behavior of the offshore wind turbine jacket supporting structure according to the soil modeling method is examined. The target sea area is the site of Southwest Sea model complex site which is promoted by the government of Korea. Interpretation is performed by analysis response spectrum and time history. The above three models were applied to the soil(Fig 1, Table 1), and the top generator was applied to 5MW offshore wind turbine.

**TABLE 1**

<table>
<thead>
<tr>
<th>Case</th>
<th>Analysis method</th>
<th>Soil application model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Response spectrum analysis</td>
<td>Winkler model</td>
</tr>
<tr>
<td>Case 2</td>
<td></td>
<td>Lumped model</td>
</tr>
<tr>
<td>Case 3</td>
<td></td>
<td>Fixed model</td>
</tr>
<tr>
<td>Case 4</td>
<td></td>
<td>Winkler model</td>
</tr>
<tr>
<td>Case 5</td>
<td>Time history analysis</td>
<td>Lumped model</td>
</tr>
<tr>
<td>Case 6</td>
<td></td>
<td>Fixed model</td>
</tr>
</tbody>
</table>

(A) FIXED MODEL  (B) LUMPED MODEL  (C) WINKLER MODEL

FIG 1. MODEL WITH SOIL RIGIDITY
II. ANALYSIS AND LOAD CONDITION

A. Design Condition of Substructure

A.1 Marine Condition

The marine conditions (Table 2) for interpretation were based on actual site survey data (KEPRI, 2014), and the extreme conditions of 50-year repetition frequency were applied.

<table>
<thead>
<tr>
<th>Type</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seabed [D.L]</td>
<td>-11.700 m</td>
</tr>
<tr>
<td>HSWL [D.L]</td>
<td>+4.399 m</td>
</tr>
<tr>
<td>MSL [D.L]</td>
<td>+0.000 m</td>
</tr>
<tr>
<td>LSWL [D.L]</td>
<td>-4.372 m</td>
</tr>
<tr>
<td>H_{max}</td>
<td>11.10 m</td>
</tr>
<tr>
<td>T</td>
<td>11.16 sec</td>
</tr>
<tr>
<td>Surge</td>
<td>0.86 m</td>
</tr>
<tr>
<td>Current</td>
<td>1.066 m/s</td>
</tr>
<tr>
<td>Marine Growth</td>
<td>100 mm</td>
</tr>
</tbody>
</table>

A.2 Soil Condition

As shown in Table 3, the southwestern coast of Korea is characterized by the soft soil of about 60m. Because of the deep soft layer, the gravity type foundation is not applied. Therefore, the jacket support structure is generally applied.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Depth(m)</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accumulation layer</td>
<td>0.0~6.2</td>
<td>Silty sand</td>
</tr>
<tr>
<td></td>
<td>6.2~11.5</td>
<td>Silty clay</td>
</tr>
<tr>
<td></td>
<td>11.5~13.0</td>
<td>Sand</td>
</tr>
<tr>
<td></td>
<td>13.0~26.4</td>
<td>Silty clay</td>
</tr>
<tr>
<td></td>
<td>26.4~46.0</td>
<td>Sand</td>
</tr>
<tr>
<td>Sedentary deposit</td>
<td>46.0~57.0</td>
<td>Sedentary deposit</td>
</tr>
<tr>
<td>Weathered rock</td>
<td>57.0~59.0</td>
<td>Weathered rock</td>
</tr>
<tr>
<td>Soft rock</td>
<td>59.0~64.0</td>
<td>Granite</td>
</tr>
</tbody>
</table>

B. Design Response Spectrum

The design response spectrum was selected by reference to Korea's "Common Application of Seismic Design Standards, 2017". The seismic performance targets are based on the I-grade earthquake with a 1,000-year recurrence interval of the collapse prevention level. The seismic zone in Korea is divided into two zones. The site is divided into 1 zone and the seismic zone factor (Z) is 0.11g. The risk factor (I) is applied from 50 years to 4,800 years, and the goal of this structure is 1,000 years (I = 1.4).

In the case of the soil, it is classified into S1 ~ S6, and the soil is applied to the S5 soil with deep and soft soil as shown in Table 3. The site amplification factor is shown in Table 4 below.

<table>
<thead>
<tr>
<th>Soil classification</th>
<th>Period amplification factor, Fa</th>
<th>Interval amplification factor, Fv</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S ≤ 0.1</td>
<td>S = 0.2</td>
</tr>
<tr>
<td></td>
<td>S = 0.2</td>
<td>S = 0.3</td>
</tr>
<tr>
<td>S5</td>
<td>1.8</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Based on the above results, the standard design response spectrum (Fig. 2) can be calculated as shown in Fig. 3 by applying the standard design response spectrum generation method of the seismic design criteria.

![Fig. 2. Drawing Method of Standard Design Response Spectrum](image-url)
Fig 3. Design Response Spectrum of Analysis Structure

Fig 4. Input Earthquake Motion
C. Time History Analysis

There are various methods for obtaining input earthquake motion for time history analysis. Typically, there are methods to obtain through deaggregation of earthquake disaster, the method to uniform hazard spectrum (UHRS), the method to obtain through ground numerical analysis, and the method using custom artificial earthquake.

At least four artificial seismic waves are to be applied in Korean highway bridge design standards. In this study, four artificial seismic waves proposed by Korea Expressway Corporation were applied (Fig. 4).

III. SOIL RIGIDITY CALCULATION AND STRUCTURE ANALYSIS

A. Winkler Model

The Winkler model is a method of applying the soil spring stiffness to each depth of the pile. In order to apply the linear spring stiffness to the pile model, the coefficient of subgrade reaction according to the depth of each pile was calculated and applied.

A.1 Coefficient of Vertical Subgrade Reaction

The coefficient of vertical subgrade reaction can be obtained as shown in Equation (1) below.

\[ k_v = k_{v0} \left( \frac{b_v}{30} \right)^{3/4} \]  

A.2 Coefficient of Horizontal Subgrade Reaction

The coefficient of horizontal subgrade reaction can be obtained as shown in Equation (2) below.

\[ k_h = k_{h0} \left( \frac{b_h}{30} \right)^{3/4} \]  

B. Lumped Model

The Lumped model has a total of six degrees of freedom to define three directions of motion and rotation in three dimensions. The displacement and load relations for these elements can be defined through the matrix, which is called the stiffness matrix (K-matrix) of the foundation. Where, K11 and K22 are the horizontal stiffness, K44 and K55 are the rotational stiffness, and K33 and K66 are the vertical and torsional stiffness, respectively. Also, K15, K24, K51, and K42 show the stiffness for the phenomenon that horizontal load and moment are coupled (Choi et al. 2014).

Fig. 5. K-MATRIX OF LUMPED MODEL

C. Model of Structure Analysis

C.1 Specification of Substructure

The support structure to be analyzed is a jacketed support structure capable of loading a 5 MW generator, and was applied as an upright jacket for the convenience of installation and construction (Fig 6).

Fig. 6. SPECIFICATION OF SUBSTRUCTURE

C.2 Modeling of Substructure

The upper generator was applied as nodal mass, and the beam model was modeled from the top of the tower to the bottom of the jacket or pile foundation (Fig 7).
D. Load Combination

In order to perform seismic analysis, a load combination is required. In Korea’s "Harbor and Fishing Port Design Standards", a load combination is proposed for each response spectrum and time history. In this study, the following load combinations were applied and the most conservative results were obtained (Table 5).

<table>
<thead>
<tr>
<th>Type</th>
<th>Dead load</th>
<th>Front direction earthquake load</th>
<th>Side direction earthquake load</th>
<th>Axis direction earthquake load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Com1</td>
<td>1.0</td>
<td>1.0</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Com2</td>
<td>1.0</td>
<td>0.3</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Com3</td>
<td>1.0</td>
<td>0.3</td>
<td>0.3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

IV. Analysis Result

A. Results of Natural Frequency Analysis

Before the seismic analysis, natural frequency analysis was performed to investigate the dynamic behavior of the structure. As a result, the mode shape of the jacket supporting structure in all models was 5th. The Winkler model which modeled the pile foundation showed the lowest frequency (Fig 8, Table 6).
B. Analysis Results of Standard Response Spectrum

Fig. 9 ~ Fig. 12 show the results of the standard response spectrum analysis. As a result of the standard response spectrum analysis, it was confirmed that the stress was the highest in the jacket braces. The shear force showed the highest value in the jacket leg, and the bending moment showed the highest value in the TP part meeting with the tower.

As a result of analysis on each soil model, it was confirmed that Winkler model showed the lowest response value in most analysis results except jacket displacement and jacket bottom maximum moment. Fixed model showed the highest response value. The lower bending moment of the jacket showed the lowest response value in the lumped model.

C. Analysis Results of Time History

Fig. 13 ~ Fig. 16 show the results of the time history analysis. The results of the time history analysis showed that the two models except for the Winkler model showed the highest stress values in the jacket braces. The Winkler model had the highest stress at the bottom of the legs. The shear force showed the highest value in the jacket leg, and the bending moment showed the highest value in the TP part meeting with the tower.

As a result of analysis on each soil model, it was confirmed that Winkler model showed the highest response value in most analysis results except shear force. Lumped model and Fixed model were found to be relatively similar.
FIG 9. RESPONSE SPECTRUM ANALYSIS RESULT OF WINKLER MODEL.

FIG 10. RESPONSE SPECTRUM ANALYSIS RESULT OF LUMPED MODEL.

FIG 11. RESPONSE SPECTRUM ANALYSIS RESULT OF FIXED MODEL.
Fig 12. Comparison of Response Spectrum Analysis Results

Fig 13. Time History Analysis Result of Winkler Model

Fig 14. Time History Analysis Result of Lumped Model
FIG 15. TIME HISTORY ANALYSIS RESULT OF FIXED MODEL

(A) MAXIMUM DISPLACEMENT

(B) MAXIMUM DISPLACEMENT (JACKET)

(C) MAXIMUM STRESS

(D) MAXIMUM SHEAR FORCE

(E) MAXIMUM BENDING MOMENT

(F) BENDING MOMENT (JACKET BOTTOM)

FIG 16. COMPARISON OF TIME HISTORY ANALYSIS RESULTS
V. CONCLUSION

In this study, time history analysis and response spectrum analysis were carried out for the offshore wind turbine jacket supporting structure according to three types of ground application method model, and comparison/examination was performed. The results are summarized as follows.

When the time history analysis was performed using the Winkler model, the most conservative results were obtained from the response values. This is because it is confirmed that the influence of the pile model on the input earthquake motion is high.

In the Fixed model, which is generally regarded as a conservative interpretation, there is no conservative response in time history analysis. However, in the case of the standard response spectrum, it was confirmed that the most conservative response value is generated.

In general, the standard response spectrum is applied to the Winkler model for seismic design of offshore wind turbine support structures. However, it was confirmed that the response value was relatively low. For a conservative review, a review with a standard response spectrum applied to the Fixed model would be required. Or, it is considered necessary to examine the analysis by applying the input earthquake motion to the Winkler model.

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