

Establishment of Jacket Structure Design Technology for Offshore Wind Farms

~ Coupling Analysis for Wind and Wave Loads, Seismic Design Methods and Design Considerations in Detailed Design ~^{*1}

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Abstract

With plans for offshore wind farms rapidly progressing in various sites in Japan, there is an increasing demand for jacket structures that excel in handling large wind turbines, deeper water, and complex ground conditions. This study focuses on the detailed design of jacket structures, requirement of items according to various design conditions, important factors in designing against wind wave and seismic loads, and structural details such as transition pieces, grouted connections, and appendages. In addition, the Ishikari Bay New Port Wind Farm, which is currently under construction, is introduced.

1. Introduction

Offshore wind power is considered a growing field in the Green Growth Strategy to achieve carbon neutrality by 2050 (Ministry of Economy, Trade and Industry)¹⁾, and the government has set a target of 10 GW by 2030 and 30–45 GW by 2040 as part of the Offshore Wind Power Industry Vision (First Phase)²⁾. Project plans are currently underway in general waters following projects in port areas, including Akita Noshiro Port, Ishikari Bay New Port, and Kitakyushu Port.

As shown in **Fig. 1**, offshore wind turbine sub-structure types include gravity, jacket, monopile, and floating types. However, expectations are increasing for the jacket-type structures, owing to factors such as increased wind turbine sizes, an increase in water depths exceeding 30 m, and the ability to deal with the ground (including bedrock). In Europe, many application examples of the jacket structure and its design method have already been established. However, it lacks established standards that meet the design conditions unique to Japan, such as the effects of earthquakes and

typhoons and ground conditions. With our participation in the “Offshore Wind Power Generation System Demonstration Research (Off the Coast of Kitakyushu City)”³⁾ managed by the New Energy and Industrial Technology Development Organization (NEDO), our company has been involved in designing multiple projects while accumulating design technology for jacket structures⁴⁾. In this study, the focus was on the detailed design of the jacket structure and presentation of the corresponding design considerations.

2. Design Flow

Figure 2 shows the design flow of the jacket structure. Analysis of the support structure with respect to the wind and wave loads (referred to as “coupled analysis”) is performed jointly with wind turbine manufacturers. Each analysis spans several months, with the number of iterations significantly impacting the design process. The design would be completed with a single analysis if the structural specifications were optimized in advance. However, in general, the process adopted involves modifying structural specifications based on the results of the first analysis before converging from the second analysis onwards. Therefore, establishing a robust structural concept at the basic design stage and setting maximum possible accurate

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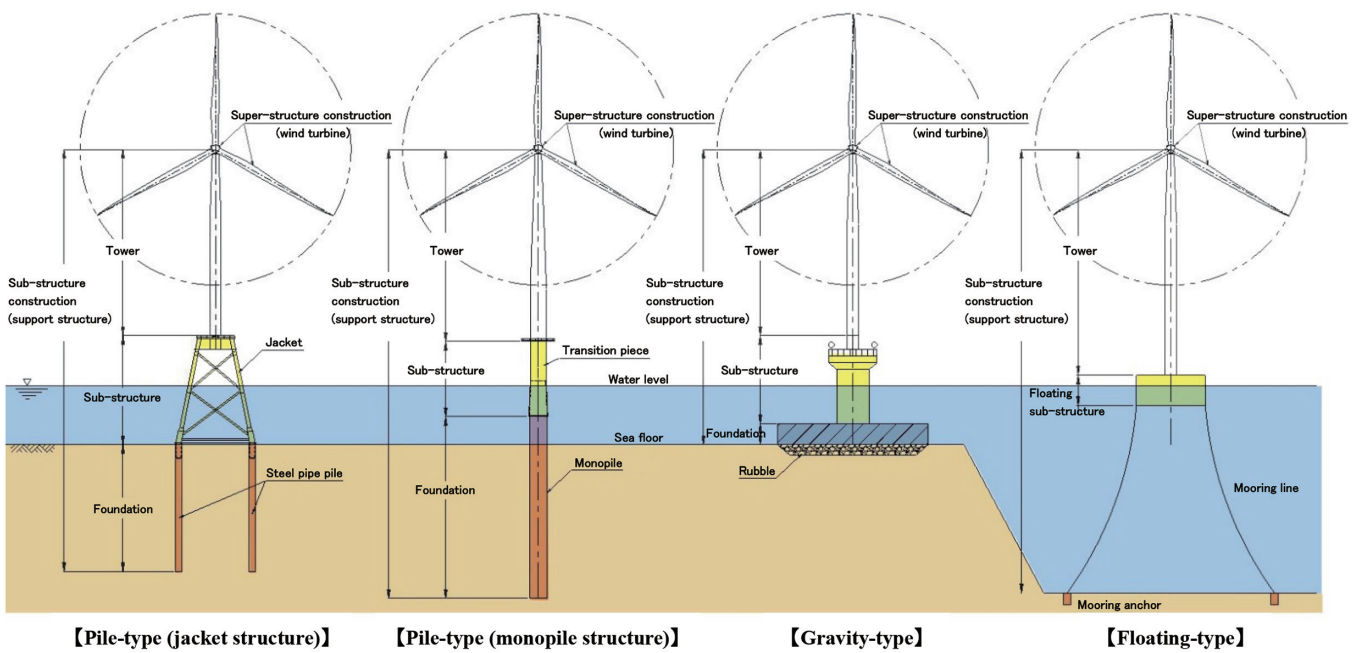


Fig. 1 Different substructure types of offshore wind turbine support structures

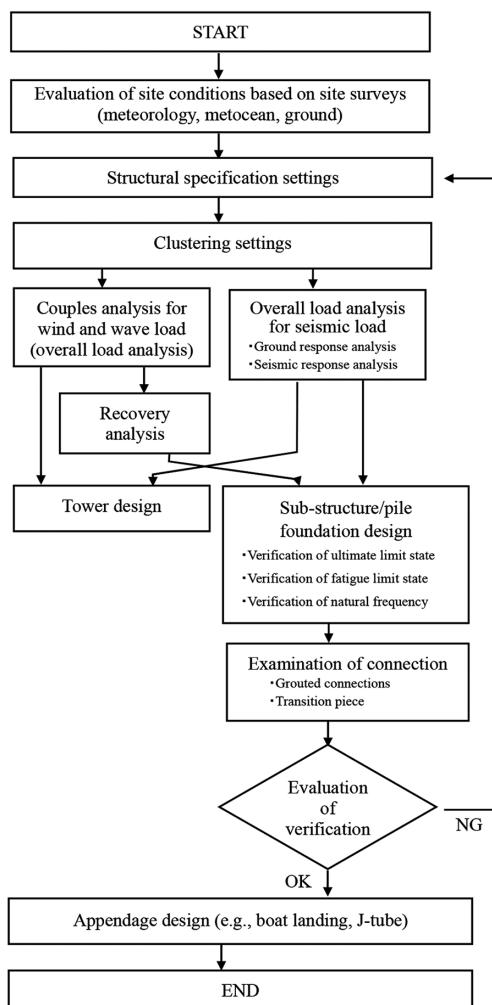


Fig. 2 Design flow for jacket structure

structural specifications in the initial design stage is important. The tower specifications could also be modified based on the first review, thus making it important to consider the change in vibration characteristics of the entire structure when reviewing and establishing the structural specifications for the second analysis.

3. Structural Specification Settings

3.1 Elevation

Figure 3 shows an overall image of the jacket structure, whereas Fig. 4 shows the structural specifications. While setting the elevation of the jacket structure, it is important to avoid subjecting the lower surface of the transition piece to wave loads and ensure compliance with the air gap regulations according to the international standard IEC61400-3²⁵⁾ in the electrical and electronic technology fields.

3.2 Leg spacing

If the leg spacing of the jacket structure is too wide, the stiffness of the support structure becomes large and fails to satisfy the allowable frequency band constraint. Meanwhile, if the leg spacing is too narrow, the required pile embedment will be long, making pile construction difficult. Therefore, setting a leg interval that simultaneously satisfies the above two constraints at the start of the design process is important.

3.3 Brace arrangement

As shown in Fig. 4, diagonal braces are placed on each structural surface of the jacket structure. When the jacket structure is manufactured and transported horizontally, the horizontal braces in addition to the diagonal braces may be placed between the lower CANs to ensure the stiffness of the jacket structure during transportation. Therefore, it is important to determine the brace arrangement taking into account manufacturing and transportation plans.

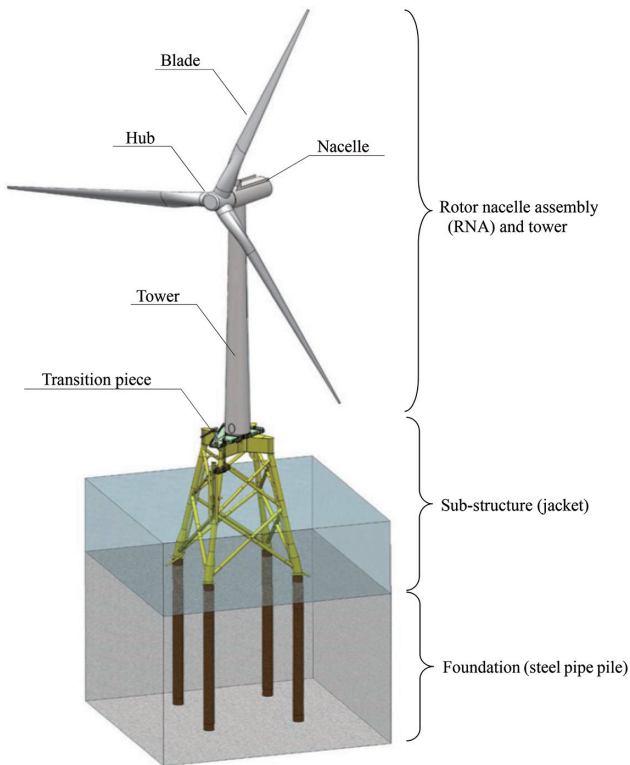


Fig. 3 Jacket structure of wind turbine support structure

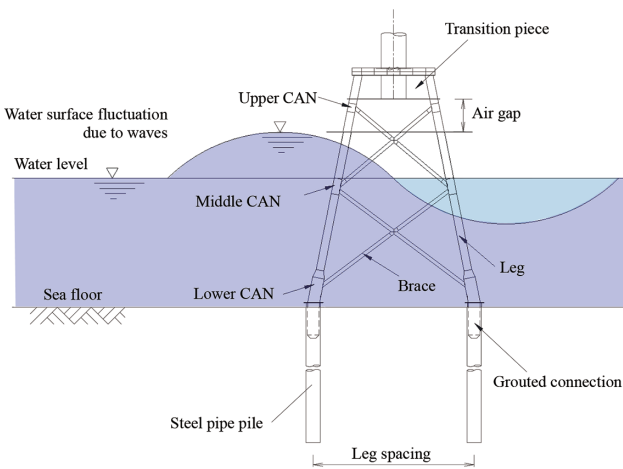


Fig. 4 Structural specifications of jacket structure

3.4 Grouted connections

The jacket and pile are integrated by grouted connections. In these grouted connections, considering the member manufacturing and pile construction errors is important for setting appropriate leg and pile diameters to ensure the spacing between the leg and pile (i.e., grout thickness) is secured. The structure of a grouted connection is discussed in detailed in Section 7.1.

4. Clustering

Generally, in offshore wind power projects, multiple wind turbines are installed simultaneously. While designing for wind and wave loads, it would be preferable to consider every turbine installation location. However, analysis for all locations would significantly

increase the design process complexity and associated costs. Therefore, a method involving clustering (grouping) study subjects by considering locations with similar water depth and ground conditions as part of the same cluster is adopted.

In addition, material procurement and manufacturing can be achieved efficiently by unifying the jacket structures in the same cluster. While applying clustering, it is important that the representative model covers all the conditions within the cluster and is designed on the safe side. When designing for a seismic load, significant differences in ground response may occur due to differences in water depth and physical properties of the ground at each location thus mandating structural analysis to be conducted for all locations without clustering.

5. Design for Wind and Wave Loads

5.1 Design conditions

(1) Load combination

The design for wind wave load should generally follow the load combinations specified in IEC61400-3²⁵⁾. **Table 1** shows an overview of the load combinations. These load combinations consider the wind turbine operating conditions as well as the metocean conditions. The “extreme” conditions used in DLC1, 6, and 7 mainly refer to extreme wind speed and extreme waves with a recurrence period of 50 years and are used to verify the ultimate limit state described in Section 5.4. In addition, the “normal” condition used in DLC1–5 mainly refers to metocean conditions such as wind speed and wind height in the power generation wind speed band of the wind turbine and is mainly used for verifying fatigue limit state, described later in Section 5.5. Hence, it is necessary to cover all the wind speeds and waves assumed in these load combinations while defining the metocean conditions. Moreover, all the combination of wind and wave directions as well as the presence or absence of errors in the yaw angle of the wind turbine must be taken into account in the load combinations. As a result, the dominant study cases alone number in the thousands. Therefore, careful consideration is required when planning the design process.

(2) Meteorological conditions

The meteorology conditions, such as the 10-min average wind speed at hub height and wind shear (difference in wind vectors at two different elevations divided by the distance between the two points) are set by field observations and analysis simulations. For example, for extreme wind speeds with a recurrence period of 50 years, the 10-min average wind speed at hub height can exceed 50 m/s. While meteorological conditions are mainly used in coupled analysis conducted by wind turbine designers, they are also used in sub-structure design when setting the wind load acting on the side

Table 1 Overview of design load case (DLC)

DLC	Design situation	Primary metocean condition
1	Power generation	Normal, extreme
2	Failure during power generation	Normal
3	During start of power generation	Normal
4	During stop of normal power generation	Normal
5	Emergency stop	Normal
6	During stop	Extreme
7	Failure during stop	Extreme

of the transition piece and during the examination of vortex-induced vibration of appendages.

(3) Metocean conditions

Metocean conditions such as tide level, water flow, wave conditions (wave height and period), and tsunami wave height, are set based on observed values in addition to past wave hindcasting information. For example, for extreme waves with a recurrence period of 50 years, the wave height can exceed 15 m, depending on the water depth at the installation point.

(4) Joint probability distribution of wind and waves and service life

While conducting a fatigue verification of a support structure, it is required to set the number of times wind and waves act repeatedly during the service period of the wind turbine. In general, the number of actions is set based on the relationship between the hub-height wind speed, wave height/cycle, and occurrence frequency (i.e., the joint probability distribution of wind and waves). This joint probability distribution is also set based on observation results; however, narrowing down the number of cases by appropriately setting the range of wind speed and wave height is important to ensure that the number of analysis cases does not become too large. In addition, while determining the design service life of the support structure, it is important to consider not only the actual operation period of the wind turbine, but also the period from construction to removal of the jacket structure, pile foundation, and wind turbine.

5.2 Analysis method

(1) Analysis flow

Figure 5 shows the analysis flow for the wind wave load. First, the sub-structure designer sets the structural specifications and wave loads for the sub-structure and foundation. Subsequently, the designer prepares the input information for coupled analysis called superelements and wave load files. Based on this information, the wind turbine designer (wind turbine manufacturer) conducts coupled analysis and designs the RNA and tower. Here, coupled analysis refers to analysis that considers the wind turbine operation and the simultaneous action of wind and waves. Next, the sub-structure designer conducts an analysis (restoration analysis) that uses the time-history sectional force at the interface points (interface load) obtained by coupled analysis as well as a partial analysis model consisting of the sub-structure, pile foundation, and soil springs to design the sub-structure and foundation. These details are described below.

(2) Creation of sub-structure/foundation structural information

Structural information of sub-structures and foundations to be incorporated in coupled analysis shall be provided to wind turbine manufacturers in the form of data generally called superelements and wave load files. Here, the superelement refers to a reduction of the mass/stiffness matrix based on the structural specifications of the sub-structure and pile foundation (reduction of dimensionality of analysis model) to improve the processing speed of coupled analysis⁶⁾. However, if the degree of reduction is incorrect, the analysis accuracy will be impaired, thus making it important to confirm in advance that the superelements gives displacement and frequency adequately agreeing with those of the analysis model before reduction.

(3) Creation of wave load information

Based on the wave conditions set in Section 5.1 (3), the wave load is evaluated as a wave force acting on the jacket member by creating an irregular time history waveform using the wave spectrum. Setting a wave spectrum is important that matches the characteristics of that site. When breaking waves occur, the influence of the impact force on the jacket cannot be ignored. Therefore, it is set with reference to the dynamic characteristics specified in IEC6400-3²⁵⁾. The wave load also needs to be reduced in accordance with the superelement, which is called a wave load file (time history) in Fig. 5.

(4) Coupled analysis

Coupled analysis uses an aeroelastic analysis program that models the rotational motion of the blades to simulate wind turbine operation. Considering this analysis includes wind turbine control information, it is typical for wind turbine manufacturers to handle this step. Representative aeroelastic analysis programs include Bladed, BHawC, and Flex5 (features of each program are described in Ref. 8).

IEC61400-3²⁵⁾ guidelines require a time history response analysis to express the vibration state of the wind turbine, and a simulation time of 600 seconds must be secured. Depending on the analysis program, the analysis may exhibit instability for several seconds after starting the analysis. Therefore, this period should be carefully excluded from the reference timeframe.

(5) Restoration analysis

Recovery analysis reproduces the coupled analysis on the sub-structure design side by inputting the interface load (obtained from

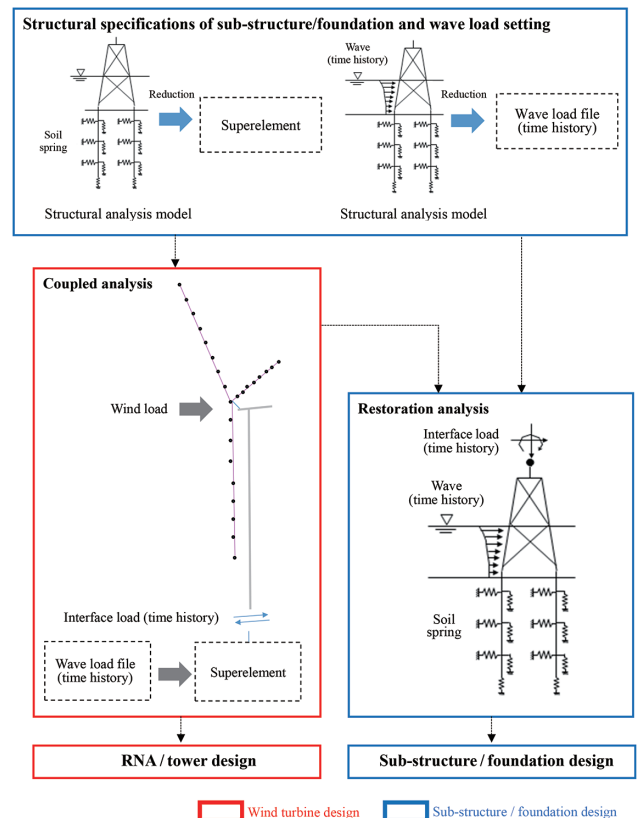


Fig. 5 Analysis flow for wind wave load

the coupled analysis) into a partial analysis model consisting of the sub-structure, pile foundation, and soil spring. Here, the analysis model before reduction is used for the restoration analysis. When implementing restoration analysis, jackets structure that have more nodes and members than the monopiles would result in a larger volume of analysis work. Therefore, key aspects in shortening the design process is to accelerate analysis processing by utilizing cloud services in addition to automating input/output data processing.

5.3 Analysis model

This section describes key points to be considered when creating analytical models for sub-structures and foundations.

(1) Overall

Figure 6 shows a structural analysis model image. The structural analysis model uses beam elements to model jacket components and piles. Discretized soil springs were installed around the piles to consider the effect of ground stiffness.

(2) Soil spring

The jacket structure resists horizontal forces such as waves and wind by the bearing force of the piles and the horizontal reaction force of the ground. Therefore, in the structural analysis model, a horizontal soil spring, vertical soil spring, and end soil spring are arranged around the pile.

Figure 7 shows the relationship between the design ground conditions and the soil spring in the structural analysis model. The design ground conditions are based on ground surveys such as boring surveys and CPT surveys; ground characteristics such as unit volume weight, undrained shear strength, and shear resistance angle are set for each stratum. Each stratum is subdivided with a thickness of approximately 1 m in the depth direction, and a soil spring is set for each. The soil spring constant is determined by considering the design ground conditions, which include the undrained shear strength and shear resistance angle. For detailed setting methods, refer to the international standard API-RP2GEO²⁶⁾ for jacket structure design in the oil and gas field.

Ground scour must also be considered when creating a structural analysis model. Scouring is a phenomenon in which the ground near the sea floor is scraped away by waves and currents. Figure 8 shows a schematic of local scour generated around piles of a jacket structure.

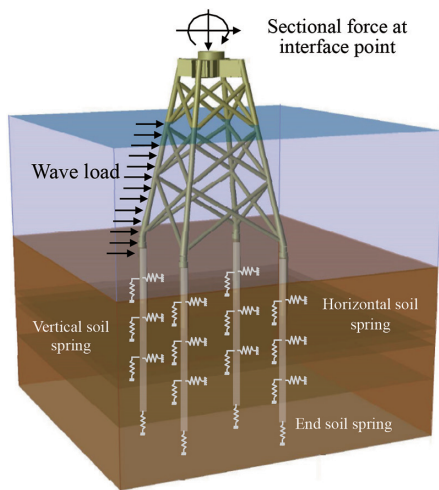


Fig. 6 Structural analysis model

If local scouring occurs during the service period, the vertical and horizontal support of the foundation will be lost. Therefore, the effects of scour must be factored into the design. Here, for the scouring depth setting method, refer to DNVGL-ST-0126²⁷⁾, which is the design standard of the third-party certification body in the field of wind power/power transmission and distribution in Europe. In structural analysis, a commonly used method for considering scouring effects is to exclude placing a soil spring within the range of scouring depth and areas where ground resistance is not expected.

(3) Damping

The damping effect of structural vibration due to the viscosity of air and seawater, deformation of steel materials, and ground is considered in time history analysis, such as coupled analysis and restoration analysis. Eq. (1) shows the basic equation of motion in the vibration problem of structures. The effects of the mass [M] and stiffness [K] of the structure as well as that of damping [C] are considered in the second term on the left side. Here, F is the external force (time history) and x, \dot{x} , and \ddot{x} are the displacement, velocity, and acceleration of the structure, respectively.

$$[M]\ddot{x} + [C]\dot{x} + [K]x = F \tag{1}$$

The damping considered in wind turbine design is decomposed

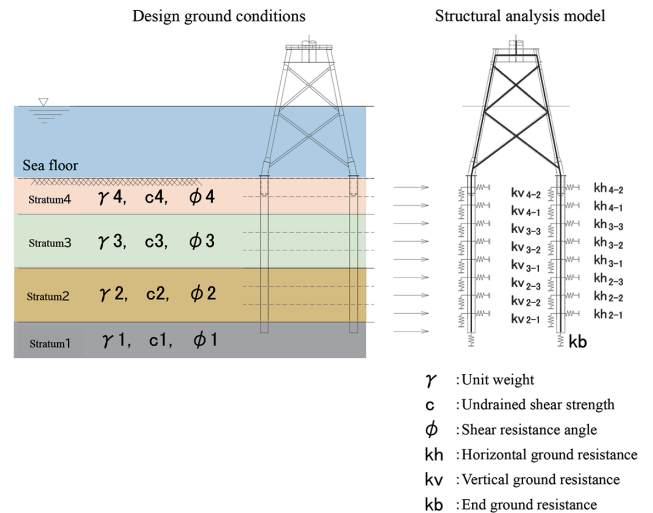


Fig. 7 Soil spring modeling for ground condition

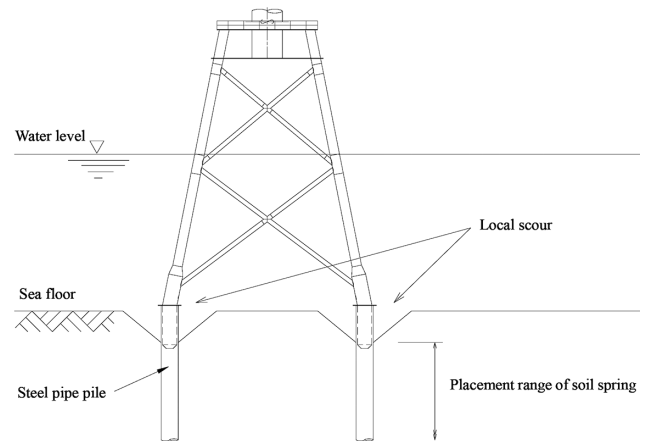


Fig. 8 Local scour around pile

into multiple factors, which are treated differently based on the analysis. Damping due to air viscosity is considered in the aeroelastic analysis (coupled analysis) because it is caused by the rotational motion of the wind turbine. For restoration analysis, the effects are included in the interface load. Damping due to seawater viscosity is ignored because it has minimal impact on the jacket structure. Structural damping and ground damping are often considered as damping proportional to the mass and stiffness of the structure (Rayleigh damping). It is preferable to set the ground damping based on the damping constant for each stratum obtained through a ground survey.

5.4 Verification of ultimate limit state

The purpose of verifying the ultimate limit state is to confirm that the sub-structure and pile foundation will remain unbroken and in a stable state against design conditions such as storms, waves, and tsunamis with a recurrence period of 50 years. The Official Explanation of Technical Standards for Offshore Wind Power (henceforth, “Official Explanation”)²³⁾ and IEC-51400²⁵⁾ do not specify any method of verifying the jacket structure in detail but recommend compliance with ISO-19902²⁷⁾ as a reliable international standard. Compliance with ISO-19902²⁷⁾ is generally implemented because domestic standards for steel pipe structures such as jacket structures are limited. International standards for jacket structures such as API-RP2A-LRFD³¹⁾ and DNVGL-ST0126²⁷⁾ may also be referred to as similar standards.

5.5 Verification of fatigue limit state

(1) Overview

With repetitive actions of wind and wave loads during power generation as well as during standby and failure, the fatigue limit state is verified by considering the fatigue damage of those components as a cumulative value. Therefore, it is important to consult with the wind turbine manufacturer before conducting the analysis to set the frequency of failures during the service period. In addition, it is necessary to add the fatigue damage that results from transportation and construction and evaluate the fatigue effect after setting the fabrication method in advance.

(2) Fatigue damage calculation method

The two types of fatigue design are based on nominal stress and hot spot stress; each should be used appropriately according to the site to be verified. The former involves obtaining the time history of the hot spot stress by multiplying the time history of the nominal stress (calculated through restoration analysis) by the stress concentration factor (SCF) of the weld. Subsequently, the stress range and number of cycles are obtained, which are then compared with the S-N curve to evaluate the fatigue life number. The S-N curve specified for each joint type must be used; for instance, DNVGL-RP-C203²⁹⁾ may be used as a reference.

The latter is based on the fluctuation range of the hot spot stress considering the stress concentration and is verified with the relevant fatigue curve. The hot spot stress is the structural stress concentration of the target part determined by the structural details, excluding the effect of welded joints. DNVGL-RP-C203²⁹⁾, etc., stipulate the method of evaluating hot spot stress for steel pipe grid points; however, for structurally complex parts such as transition pieces, a FEM analysis must be conducted to obtain the hot spot stress. **Figure 9** shows an example of hot spot stress concentration. The stress values at points $0.5t$ and $1.5t$ (t : plate thickness) away from the weld toe to

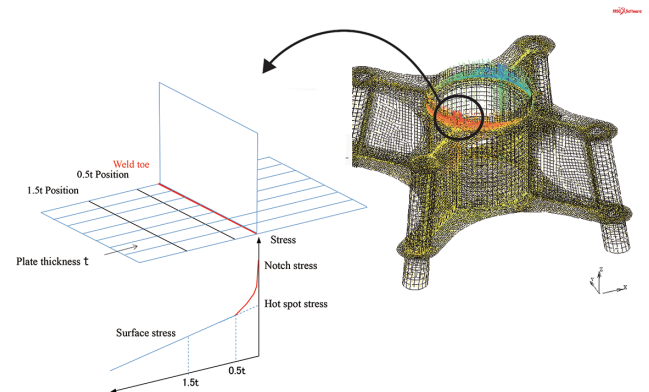


Fig. 9 Calculation of hot spot stress by FEM analysis

be verified are extracted, with a linear extrapolation of the two points conducted to calculate the hot spot stress. Refer to the guideline and commentary on the design of support structures for wind power generation equipment³⁰⁾ and DNVGL-RP-C203²⁹⁾ for detailed methods.

(3) Fatigue grade setting

In jacket structures, verifying the fatigue of the long welds of legs and welds of grid points between legs and braces is important for determining the member dimensions. DNVGL-RP-C203²⁹⁾ states that when butt welds are welded from both sides, grade D is applied for both sides and grade F3 is applied when welded from the outer side. Welding from one side increases fatigue damage; therefore, welding from both sides is generally adopted; In that case, it is essential to coordinate the manufacturing procedure with the manufacturer at the start of design, such as the joining points, welding method, access method for welding workers, welding work environment. If welding from one side, nondominant locations in the fatigue design must be selected. In addition, in areas with severe fatigue damage of the weld toe, fatigue life can be improved by performing the finishing process with a grinder to eliminate the undercut or by applying hammer peening. However, when performing these methods, discussing workability with the manufacturer in advance is necessary. In the future, there will be increased expectations for applying a method to enhance fatigue life, which involves forcibly introducing the compressive residual stress using ultrasonic impact treatment (UIT)¹⁰⁾; this method has already demonstrated its effectiveness at the D runway pier of Tokyo International Airport.

While conducting fatigue verification, it is important to evaluate fatigue damage assuming that a misalignment may occur in the plate joint due to manufacturing and construction errors because the stress concentration due to the misalignment impacts fatigue damage; the misalignment assumed in the design should essentially match the manufacturing control value. Therefore, it is important at the start of the detailed design to check the manufacturable dimensions like pipe length and plate thickness, which are considered in specifying the locations of the weld joints.

5.6 Verification of natural frequency

The wind turbine manufacturer may indicate an allowable frequency band for the natural frequencies of the entire structure to avoid the resonance of rotational motion of the wind turbine and the support structure. **Figure 10** shows an example of setting the allowable vibration band. In this case, the first natural frequency of the

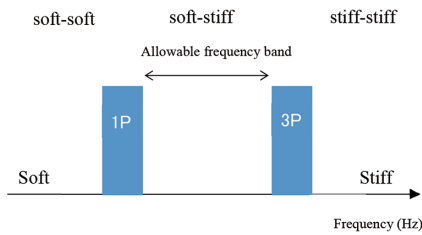


Fig. 10 Allowable frequency band^{3,4)}

entire structure consisting of the RNA, tower, sub-structure, and foundation is designed to fall within the soft-stiff range sandwiched between the rotational frequency of the rotor (1P) and the frequency of the three blades passing through the tower (3P). The jacket structure has greater stiffness than the monopile structure; therefore, the 3P side is the dominant factor. When the frequency does not fall within the allowable frequency band, a review of the structural specifications of the jacket must be performed with measures to reduce stiffness. However, if the structural specifications are changed during the implementation of the detailed design, a considerable amount of additional work is required; therefore, setting the structural specifications within the allowable frequency band is important at the initial design stage.

6. Design for Seismic Load

6.1 Input seismic motion

The Official Explanation²³⁾ requires verifying three types of seismic motions in the design: spectrum-compatible waves, observed waves, and site seismic waves (port seismic waves). An overview of each is given below. For the detailed setting methods, refer to the Official Explanation²³⁾.

(1) Spectrum-compatible waves

Spectrum-compatible waves are time-history waveforms that satisfy the relationship between the shaking intensity and natural frequency of the structure as stipulated by the Electricity Business Act. While setting the time-history waveform of the spectrum-compatible wave, consideration of multiple phase characteristics and two different seismic magnitudes is necessary. For the phase characteristics, subduction-zone earthquakes and epicentral earthquakes are selected, respectively; for seismic magnitudes, two types of seismic motions (rare seismic motion with a recurrence period of 50 years, and extremely rare seismic motion with a recurrence period of 500 years) are considered as structure shaking intensity differences.

(2) Observed waves

For the observed waves, strong motion records observed in Japan and overseas in the past were used. Multiple selections were made from California earthquakes (El Centro, 1940; Taft, 1952), the 1968 Tokachi-Oki earthquake, and the 1978 Miyagi-ken-oki earthquake. As with the spectrum-compatible waves, the observed waves require the consideration of two types of seismic magnitude (rarely occurring seismic motion and extremely rarely occurring seismic motion), with the maximum velocity amplitudes of previous strong motion records normalized to 0.25 and 0.50 m/s, respectively.

(3) Site waves (port seismic waves)

Site waves are set based on the actual measured value of the seismic motion at the construction site, as well as the seismic waves published on the website of the Port Facility Laboratory, Port Facili-

ties Division, National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure, Transport and Tourism are generally used.

6.2 Load combinations

The influence of the support structure on the seismic load is evaluated by time-history response analysis using an overall analysis model consisting of the RNA, tower, sub-structure, foundation, and soil spring (henceforth, “seismic response analysis”). The loads that must be considered in the analysis include the seismic load as well as the wind and wave loads; in addition, the operating state of the wind turbine also needs to be considered. **Table 2** shows an example of the load combinations based on IEC61400-3²⁵⁾ and the Official Explanation²³⁾. In addition to these, it is necessary to consider the combination of the earthquake and wind wave action directions.

In recent years, extremely rare earthquakes may become the dominant case owing to the increase in the size of wind turbines; as mentioned in Section 6.1, it is necessary to consider various types of seismic waves and the above-mentioned load combinations. As the analysis require a significant volume of work, it is important to identify dominant seismic waves and load combinations at an early stage and determine the structural feasibility of the support structure.

6.3 Ground response analysis

(1) Purpose of ground response analysis

Of the seismic waves mentioned in Section 6.1, spectrum-compatible waves and site waves are defined as seismic ground motions against the engineering bedrock (bedrock waves). Here, the engineering bedrock is assumed to be a “stratum that is not significantly affected by the ground” at a certain underground depth, and the Official Explanation²³⁾ specifies that the engineering bedrock should be defined as a stratum in which the shear elastic wave velocity propagating in the ground exceeds 400 m/s. In general, hard cohesive soil, gravel-mixed soil/sand, or the bedrock layer can serve as the engineering bedrock. It is also possible to calculate the shear elastic velocity from the N-value (numerical value that serves as a standard for determining the compactness and strength of the soil and is obtained from a standard penetration test on-site). However, according to the ground evaluation and Q&A for Building Foundation Structure Design³³⁾, the relationship between the two shows large variation. Therefore, when conducting ground surveys, it is preferable to conduct PS logging in addition to the standard penetration test to directly measure the shear elastic velocity and identify the position of the engineering bedrock.

When this bedrock wave passes through the ground and gives a seismic action to the structure, the ground response may show an

Table 2 Sample of load combinations for seismic response analysis

CASE	Design situation	Meteorology condition	Metoccean condition
A	Normal operation	Rated wind speed	Annual average wave height
B	Emergency stop	Rated wind speed	
C	Idling	No wind/cutout wind speed	

Rated wind speed: Specified wind speed at the hub height where the rated power of the wind turbine is generated

Cutout wind speed: Maximum wind speed that the wind turbine can generate electricity

amplifying effect of the seismic motion. Therefore, evaluating the effects of ground amplification is necessary before earthquake response analysis (henceforth, “ground response analysis”). When implementing ground response analysis, a model for only the ground is generally constructed, and time history response analysis is conducted. The observed waves are seismic motions assumed to be input to the sea floor (“surface waves”). Therefore, ground response analysis is not conducted and the ground amplification effects are also not considered in earthquake response analysis.

(2) Ground response analysis method

Figure 11 shows the ground response analysis model. As mentioned in 5.3(2), information such as unit volume weight, shear elastic modulus, and shear elastic wave velocity of the stratum is obtained from ground surveys conducted in advance to create a design ground, based on which a ground response analysis model is developed. If the strata are piled up almost horizontally, a one-dimensional free ground model is adopted; however, if the strata tilt impact cannot be ignored, a two-dimensional model should be used.

Grounds consisting of sand layers, clay layers or the like generally exhibit nonlinearity. Therefore, the equivalent linearization method is generally used as the ground constitutive law in the ground response analysis; however, a nonlinear model should apply where the applicable range of the equivalent linearization method (1% or less) is exceeded. The details of the equivalent linearization method can be found in “Seismic response analysis and design of buildings considering dynamic soil-structure interaction”²⁴⁾. The relative displacement and relative velocity with respect to the bedrock are obtained as a result of the ground response analysis. Their utilization methods are described in the next section.

(3) Handling of liquefaction

When ground liquefaction occurs during an earthquake, ground stiffness reduces significantly, ground deformation tends to increase, and ground reaction force tends to decrease. The ground amplification effect differs depending on whether liquefaction occurs, making it difficult to determine which case is dominant. Therefore, conducting analysis for both cases is necessary. The method of multiplying the ground stiffness by the reduction rate is frequently used to consider the effect of liquefaction. For the reduction rate setting method, reference may be made to “Seismic response analysis and design of buildings considering dynamic soil-structure interaction”²⁴⁾.

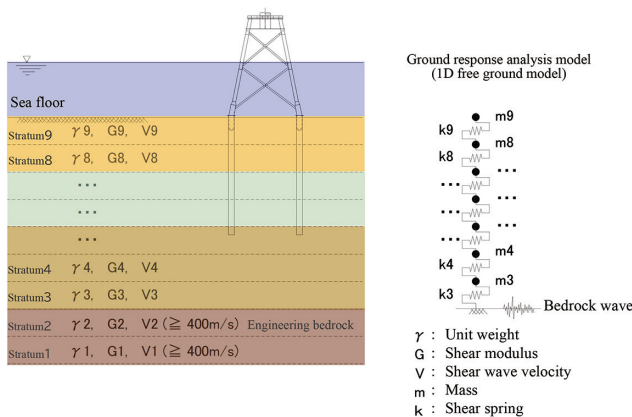


Fig. 11 Ground response analysis model

6.4 Seismic response analysis

(1) Analysis model

Figure 12 shows a conceptual diagram of seismic response analysis. The structural analysis model is an overall model that consists of a sub-structure, pile foundation, tower, and RNA to reproduce the vibration properties of the entire structure. To simultaneously consider the seismic force acting on the structure and the ground amplification effect, the inertial force due to the acceleration of the bedrock wave (bedrock acceleration) is input to the entire analysis space, and the relative displacement with the bedrock obtained by the ground response analysis is input into the soil spring of the structural analysis model.

(2) Soil spring

The soil spring used in the seismic analysis model involves an evaluation of the effects of seismic motion transmitted from the ground to the support structure. Therefore, the method of evaluating dynamic shear stiffness from the shear elastic wave velocity of the ground is commonly used instead of evaluating from the undrained shear strength and shear resistance angle of the ground, as mentioned in Section 5. The evaluation method based on wave theory is generally used as a method for setting the dynamic shear stiffness. The thin-layered element method may also be applied when precisely evaluating the ground behavior. The thin-layered element method divides the ground into thin layers and discretizes the wave equation with the assumption that each thin layer has uniform and homogeneous material properties that precisely express the relationship between the displacement of the stratified ground and the load. For examples of studies on jacket structures for offshore wind power, refer to References 11) and 12).

(3) Verification of member stress

The Official Explanation²³⁾ requires the support structure to not be damaged by rarely occurring earthquakes and not fall over or collapse in extremely rarely occurring earthquakes. The jacket structure a truss structure comprising legs and braces has high structural stability; therefore, the structure can be prevented from falling over or collapsing even if the members are partially plasticized. However,

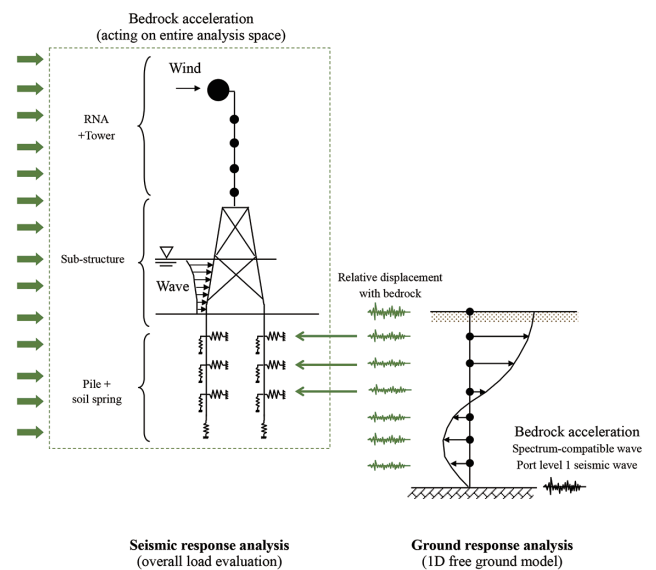


Fig. 12 Concept of seismic analysis

er, assuming an immediate restart of operations after the earthquake, it is challenging to identify the plasticized parts and evaluate their degree of damage. Therefore, a method of keeping the member stress within the elastic range even against extremely rarely occurring earthquakes is considered a method of designing on the safe side. However, evaluating the adoption of this design method is required, considering the operation policy of the power generation facility. For verification methods of member stress during an earthquake, reference may be made to API-RP2A-WSD³²⁾.

7. Examination of Structural Details

7.1 Design of grouted connection

(1) Structural overview

The grouted connection is an important part that transmits the axial force and bending moment generated in the legs of the jacket structure to the pile. **Figure 13** shows an overview of the structure of a grouted connection. A gap of approximately 100–200 mm between the steel pipe and leg is filled with a 100-MPa-class compressive strength grout material. European manufacturers have led the development of grout materials; however, the development of grout materials with similar strength¹³⁾ is also underway in Japan. In addition, shear keys are arranged on the inner surface of the outer side and the outer surface of the inner pipe. The axial force is transmitted from the leg to the pile by the compression strut of the grout between the shear keys.

(2) Design method

The basic method for verifying the structural safety of grouted connections is to satisfy simple evaluation formulas such as the “verification of shear force of shear key for axial force,” “verification of contact pressure for bending moment and shear force,” and “verification of fatigue damage for cyclic loading” stipulated in DNVGL-ST-0126²⁷⁾. In Europe, it is common to conduct examinations using these evaluation formulas and conduct additional finite element method to verify the safety of the grouted connection with construction errors between legs and piles.

7.2 Design of transition piece

(1) Structural overview

The transition piece is important for transmitting the bending moment at the base of the tower to the leg of the jacket by axial force. Various forms such as a cane structure and a box girder structure have been adopted in Europe.

(2) Design method

The transition piece serves as a connection node with the tower; therefore, information on the tower, connection flange, etc. shall be provided by the wind turbine manufacturer, and then the design shall proceed with mutual consultation. In addition, the transition piece structure is complicated; thus, finite element analysis is generally used to evaluate the safety of each member. The transition piece also functions as a support structure for the external and internal work floors. Therefore, it is important to proceed with the examination together with the appendages.

7.3 Appendage design

(1) Arrangement of appendages

Figure 14 shows an example of the arrangement of appendages in a jacket structure. This figure shows the external working floor, landing, access ladder, J-tube, and aboardage equipment; in addition,

work floors, grout pipes, temporary construction works, and other appendages for construction will be installed inside the transition piece.

(2) Boat landing and access equipment

Aboardage equipment generally is placed on the opposite side of the main wave direction after considering the steerability of the access vessel when it berths. If there is a large height difference from the docking position to the external work floor, a landing will be provided in the middle, considering the safety of workers when ascending and descending. The rest platform is designed against the aboardage force and wave load of the access vessel in service. When waves act on the landing, the upward wave force (slamming force) shall also be considered.

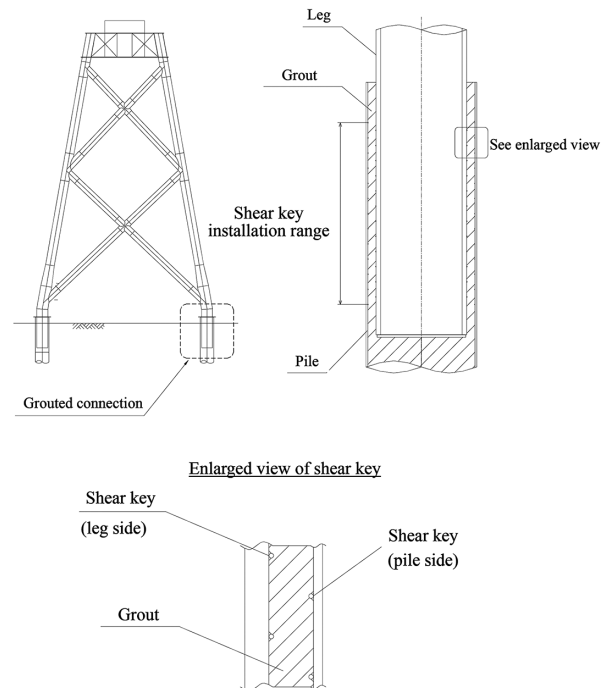


Fig. 13 Grouted connection

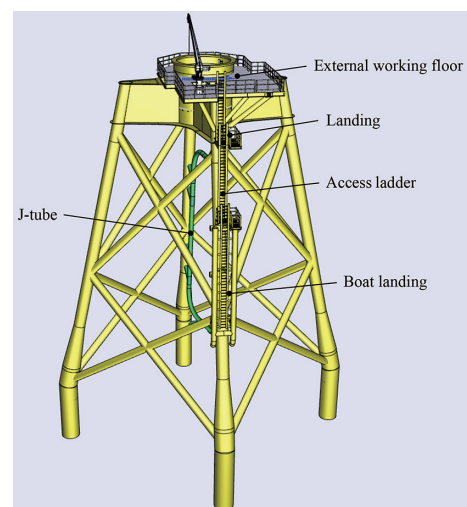


Fig. 14 Sample of appendages

(3) J-tube

Protective steel tubes (J-tubes) containing cables are placed at one or two locations on each WTG. Wind and wave loads act on the J-tube. Therefore, it is important to verify the ultimate and fatigue limit states as well as the arrangement method and spacing of support materials to ensure no damage is caused due to vortex-induced vibration.

(4) External working floor

The shape of the external working floor is determined to secure the working space necessary for replacing the equipment inside the turbine and the space for evacuating from the nacelle upper escape port in an emergency. Stationary crane systems for unloading should consider the access vessel aboardage to the aboardage equipment and the unloading position on the external platform. Various types of equipment, such as navigation lights, lighting equipment, signboards, and monitoring systems, are also installed on the external working floor and influence the design of the transition piece. Therefore, coordinating with the business operators and wind turbine manufacturers at an early stage is important.

7.4 Corrosion protection design

(1) Overview

The specifications of the anti-corrosion system of the jacket structure are determined by considering factors such as the corrosive environment, years of service, performance, cost, maintenance, and management. In general, there are many cases where the coating is applied to the air and splash tidal zone, with cathodic protection applied to the underwater part.

(2) Paint coating

To prevent corrosion of the steel material, the coating is applied to the outer surface of the steel pipe in advance at the factory manufacturing stage. The Port and Steel Structure Anti-Corrosion Repair Method Manual²¹⁾ sets coating specifications based on the international standard ISO12944²²⁾ for corrosion protection of offshore structures; these specifications may be used as a reference. If the design service period exceeds the service life of the selected coating material, a method that considers the corrosion allowance in the thickness of the steel material may be considered a method of designing on the safe side. The service life of the coating material may be set by referring to the Port and Steel Structure Anti-Corrosion Repair Method Manual²¹⁾; however, a comprehensive evaluation should be made based on the performance of the coating material used and the accelerated test specified in ISO12944²²⁾.

(3) Cathodic protection

Cathodic protection is classified into two types: galvanic (sacrificial) anode method and impressed current method. For jacket structures, the galvanic anode method is often adopted from the perspectives of performance and maintenance; however, in Europe, in some cases, the impressed current method is adopted from the viewpoint of SDGs.

8. Conclusion

The authors are currently involved in the construction of the Ishikari Bay New Port Wind Farm together with Shimizu Corporation. This is the first project in Japan to use a jacket structure, and on its completion, it will use an 8-MW wind turbine, one of the largest in Japan. At the time of this publication, the construction of steel

pipe piles (Fig. 15) has been completed, while the construction of the jacket structure (Fig. 16) is underway. In FY2023, the construction of the jacket structure and wind turbine will be completed, with the aim of starting operations within the same year.

This project acquired design certification from Nippon Kaiji Kyokai in February 2022; however, at the time of review, there were no precedent cases of jacket structure certification in Japan. That was why careful examinations were required for each technology, such as the ground evaluation method. Various challenges were encountered because of the start from an unprecedented position. However, valuable experience has now been gained by establishing a precedent for offshore wind turbines in cooperation with third-party organizations.

In the future, offshore wind power generation will involve larger wind turbines and deeper water. Major issues in the future will include the pursuit of structural feasibility and economic rationality, as well as the enhancement of manufacturing and construction capabilities. The aim is to combine our experience gained from NEDO demonstration research, Ishikari Bay New Port Wind Farm, etc., with the marine design and construction technology developed over the past 50 years to contribute to the expansion and popularization of domestic offshore wind power generation in the future.



Fig. 15 Installation of piles at the site



Fig. 16 Jacket structure under construction at Nippon Steel Steel Structure Co., Ltd.

Acknowledgments

The authors would like to thank everyone involved with Green Power Ishikari LLC, Green Power Investment, and Ramboll for their cooperation in the publication of this paper.

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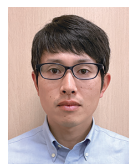
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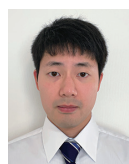
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