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JFE Engineering's Initiatives in Offshore Wind Power Foundation Business

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Abstract:

In recent years, offshore wind power generation has been introduced in Japan. In order to further spread this business, it is necessary to improve the design techniques of the foundation structure. In Europe, which is a leader in this field, the superelement approach, in which a wind turbine and a foundation are modeled separately, is widely adopted for the design. The validity of this approach is confirmed in this paper. In addition, there are no companies capable of manufacturing monopile foundations in Japan. As a result, project owners are forced to procure them from overseas. To establish the first monopile manufacturing business in Japan, we are working on the construction of a monopile factory and establishment of shipping, transportation, and a quality control system of monopiles.

1. Introduction

Offshore wind power generation is considered to be the key technology for achieving the transition to renewable energy as the main source of electric power, and introduction is expanding worldwide, particularly in Europe. In Japan, the government has announced a policy of project formation with targets of 10 GW by 2030 and 30 to 45 GW by 2040. Wind farm operators (electricity generation utilities) have already been selected for promotion zones at four locations in Japan, and site construction is expected to begin in 2026.

The types of foundations used in offshore wind power generation are classified as the bottom-mounted type, which is installed in shallow water areas, and the floating type, which is used in deeper water. Bottom-mounted foundations further classified as three types, the monopile type, the jacket type and the gravity type. It is assumed that development will begin first from the bottom-mounted type in shallow waters, and the monopile type, which has a relatively inexpensive construction cost, will become the main stream. It is thought that the jacket type will be applied successively from sites with a bedrock sea bottom and deeper water, where monopile construction would be difficult, and will then gradually expand.

Because the monopile foundation is an ultra-large steel pipe structure with a diameter on the order of 10 m and a unit weight of around 1 000 t, there are currently no manufacturers in Japan that are capable of producing monopiles. On the other hand, Japanese manufacturers, beginning with JFE Engineering, have an extensive track record of the fabrication of jacket-type structures, but jackets for offshore wind power are a completely new field. JFE Engineering plans to construct a new factory for monopiles, which are expected to become the main type of foundation in the future. JFE Engineering also aims to create a production system for the full line-up of bottom-mounted foundations for offshore wind power by producing jackets, an area in which the company already possesses a wealth of experience, after acquiring the design techniques necessary in offshore wind power.

This paper describes the development of design techniques for jacket-type foundations for offshore wind power and JFE Engineering's initiative in the construction of Japan's first domestic monopile factory.

2. Development of Design Techniques for Offshore Wind Power Foundation Jackets

2.1 Foundation Design Work in the Offshore Wind Power Generation Projects

In offshore wind power generation projects in Japan, the operator is legally required to obtain wind farm certification (hereinafter, design certification) as

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the certification necessary for approval of the notification of the construction plan based on Japan's Electricity Business Act. The certification process includes an assessment of the environmental conditions at the site where the wind farm is to be constructed and a design conformity assessment of the wind turbine and its supporting structure based on those environmental conditions. The review for certification is conducted by the Expert Panel on Wind Turbines of the Ministry of Economy, Trade and Industry (METI). Although a period of roughly 1 to 1.5 years is required for this review, the fact that construction can begin quickly after design certification and financial close will lead to an early start of operation of the power generation project, and thus is extremely important for the profitability of the project. For this reason, the detailed design of the foundation structure is also carried out in parallel with the review for certification.

In the design of foundation structures for offshore wind power, a coupled wind-wave analysis that can properly assess the effects of the wind load transmitted from the wind turbine and waves is necessary. Since the coupled wind-wave analysis involves several thousand cases and requires an extremely high level of technology, including dynamic analysis, separated analysis (superelement analysis), fatigue design and so on, particularly in the case of jackets, there are very few companies in Japan which are capable of this kind of design, and in many cases the design work is done by a design consultant in Europe.

JFE Engineering believes it is extremely important to have technical capabilities for jacket design that can support the business operator or the EPC contractor from the detailed design stage so as to enable a smooth start of fabrication after the operator obtains design certification.

2.2 Offshore Wind Power Foundation Design in JFE Engineering

JFE Engineering began full-scale technical development of offshore wind power foundation design around 2010 and has accumulated technologies related to the load characteristics and structural characteristics of foundations for offshore wind power, which are significantly different from those of general civil engineering structures, by supporting wind farm certification in a certain project.

As an example, the following describes the verification of the validity of the superelement approach[1], in which the wind turbine structure and the foundation structure are modeled separately.

2.2.1 Model and analysis code

For this verification, an analysis method using an integrated model of the turbine structure and the foundation structure (hereinafter, integrated analysis) and the superelement approach will be compared. A Bladed[2] standard 5 MW wind turbine is applied as the wind turbine model, and a jacket is used as the foundation. In the integrated analysis, modeling of the wind turbine and the foundation structure, and a coupled wind-wave analysis are all carried out with Bladed. In the superelement approach, Bladed is used only in modeling of the wind turbine structure side and the coupled wind-wave analysis, and a code that was devel-

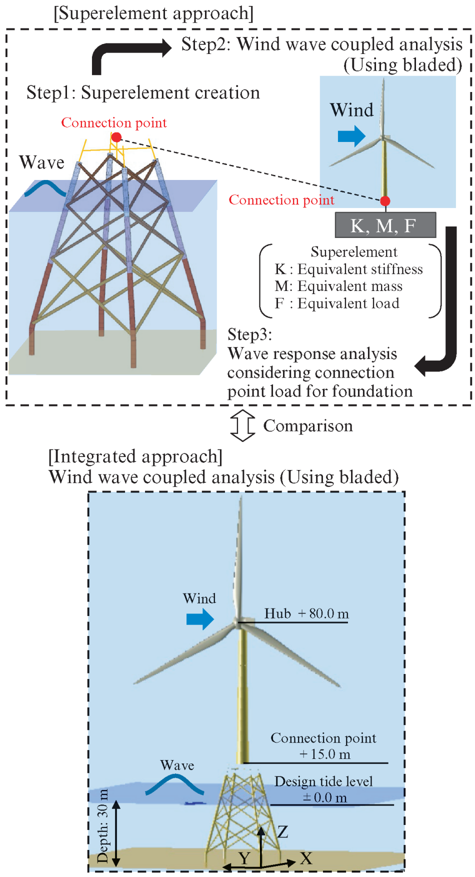


Fig. 1 Comparison of superelement approach and integrated approach

Table 1 Analysis condition

Wind	Wave	Static load	Mass
Turbulent wind, V = 47.5 m/s, Yaw error θ = 8°	Constraint non-linear waves applied Pierson-Moskowitz wave spectra, Hs = 7.5 m, Tp = 12 sec, Wave direction = 0°	1) Dead load 2) Buoyancy load	1) Structual mass 2) Added mass
Damping	Pδ effect	Simulation time	Time step
Rayleigh damping	Considering	600 sec	0.01 sec

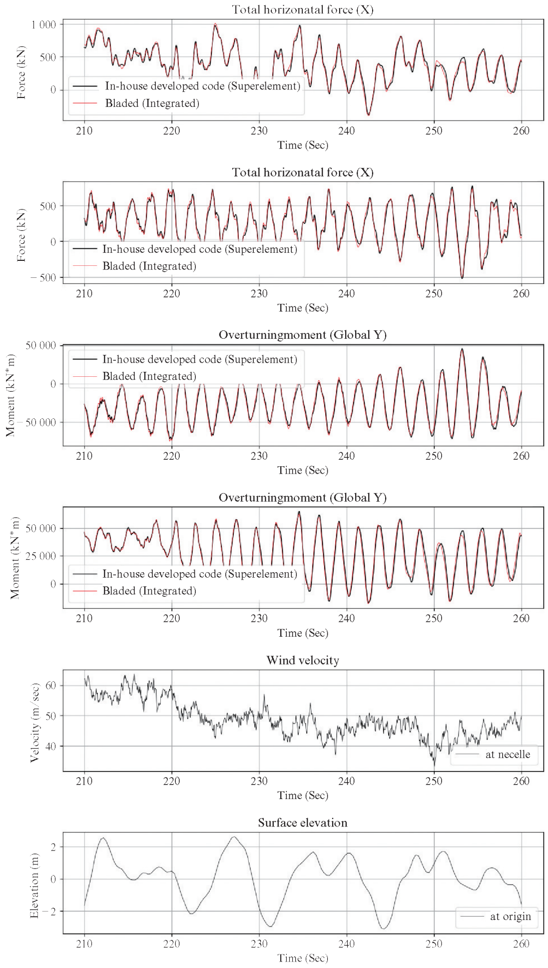


Fig. 2 Total horizontal force and total overturning moment, etc. (210 to 260 sec)

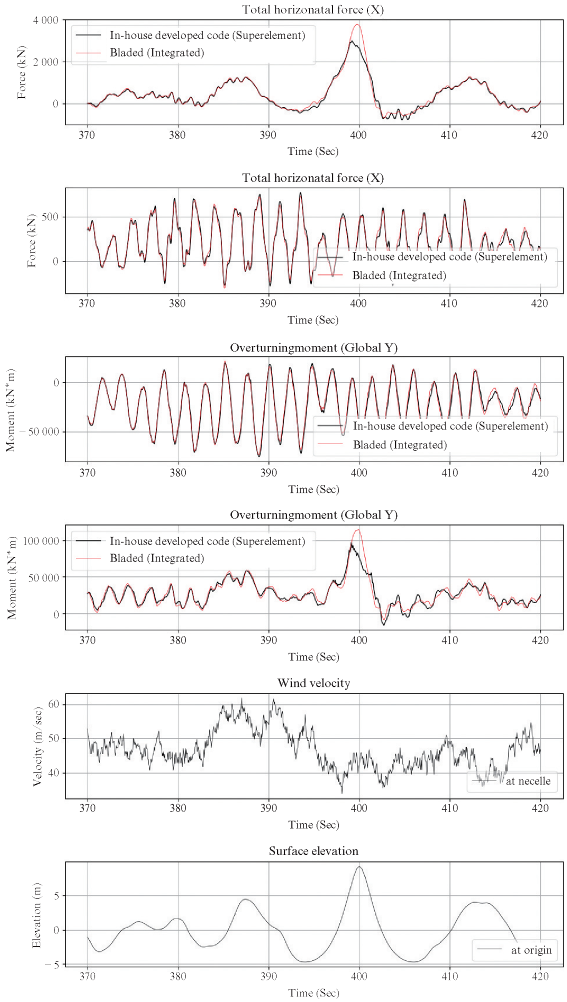


Fig. 3 Total horizontal force and total overturning moment, etc. (370 to 420 sec)

oped in-house by JFE Engineering is used for all other modellings and analyses. The superelement approach is used to express the dynamic characteristics of the foundation structure. A comparison of the integrated approach and the superelement approach is shown in **Fig. 1**.

2.2.2 Analysis conditions

The analysis conditions are shown in **Table 1.**

Here, the yaw error of 8° indicates the misalignment of the rotor direction and the wind direction. The load conditions were determined so as to satisfy DLC6.1 equivalent as specified in IEC 61400–3–1[3].

In the integrated analysis using Bladed, a stream function wave equivalent to the maximum wave height is embedded at 400 s while constructing random wave fields. In the superelement approach, the wave force is calculated by reproducing the wave field of Bladed.

2.2.3 Comparison of total horizontal force and total overturning moment

Figure 2 and **Figure 3** show the time histories of the total horizontal force and total overturning moment at the sea bottom surface. The target analysis times of the two figures are 210 to 260 s and 370 to 420 s, respectively. The time history graphs of the wind velocity and water level change (surface elevation) are also shown for the same times.

Comparing the superelement approach and the integrated approach, it can be understood that the two analysis methods show good overall agreement. However, a difference can be seen at around 400 s. This difference occurred because it was difficult to reproduce the wave field for the time zone where the stream function wave was embedded by the superelement approach. When using the superelement approach in practical work, it is not necessary to reproduce the wave field around the embedded wave because random wave fields are constructed considering embedded waves on the foundation structure side and the wave force is calculated in Step 1 and Step 3 of Fig. 1. Therefore, this difference does not affect practical work.

2.2.4 Comparison of section forces at connection point

Figure 4 shows the time history graphs of the section forces at the connection point. The target time of the analysis is 370 to 420 s, and all 6 force components are shown, that is, axial force, shear force (2 components), torsion and moment (2 components). Comparing the results, although good overall agreement was obtained, a difference can be seen around the time of 400 s. As in the comparison of the time history graphs of total horizontal force and total overturning moment, this difference is also attributed to the difficulty of reproducing the wave field in the time period that includes the embedded wave. However, these differences do not occur in practical work, as it is not necessary to reproduce the wave field.

2.2.5 Result of validation of superelement approach

Comparing the results of the integrated approach and the superelement approach, the total horizontal force, total overturning force and all section forces at the connection point showed good agreement, confirming that the superelement approach is a valid analysis method.

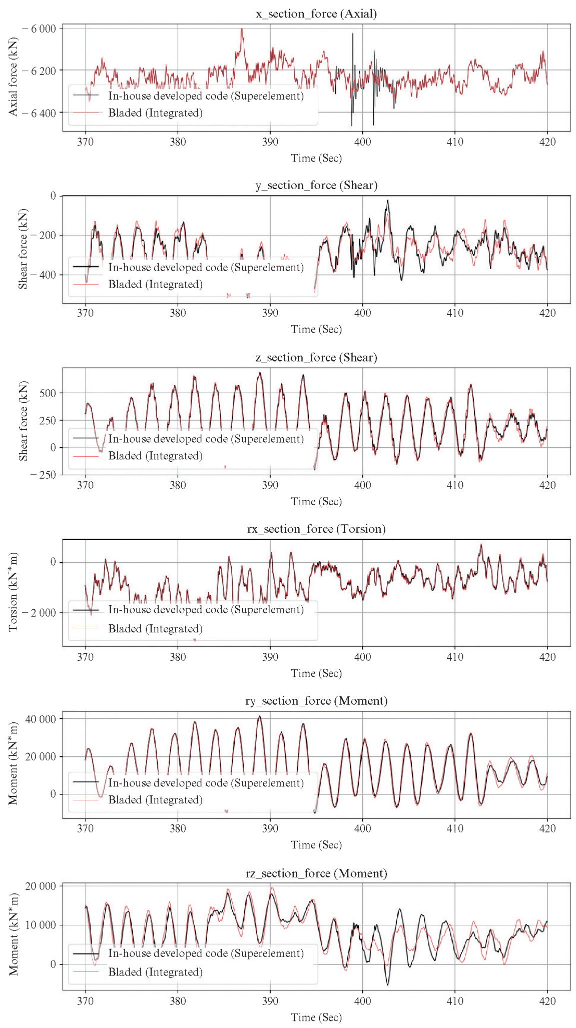


Fig. 4 Section force at connection point (370 to 420 sec)

3. Construction of Monopile Factory

3.1 Forecast of Market for Offshore Wind Power Foundations and Production Capacity of New Factory

In its monopile manufacturing business, JFE Engineering plans to manufacture monopiles and transition piece primary tubes at a new factory to be constructed in Kasaoka (hereinafter, new factory) and assemble the transition pieces at its existing Tsu Works. The appearance of a transition piece and monopile is shown in **Fig. 5**. The new factory will be constructed with the aim of starting operation in FY 2024, when Japan's offshore wind power project enters its full-scale phase.

The production capacity of the new factory was set to enable production of the foundations for one wind farm project in one year, assuming an average power generation scale of 500 MW. Thus, in the case of foundations for 10 MW wind turbines, the actual production volume will be 50 sets/year, or 80 000 to 100 000 tons. As the scale of the monopile market in Japan, orders are expected to trend at approximately 160 000 tons/year from fiscal 2027 onward.

3.2 Overview of Monopile Factory

The new factory will be located 1.5 km south of the Fukuyama Pipe Mill, which produces large-diameter welded steel pipes JFE Steel's West Japan Works (Fukuyama) in Kasaoka City. **Figure 6** shows the location of the new monopile factory, and **Fig. 7** shows the overview and a schematic diagram of the plant.

- Site area: 20 ha (430×460 m)
- Production capacity - maximum diameter: Approx. 12 m
- Monopile storage capacity: 22 to 30 pieces (In case

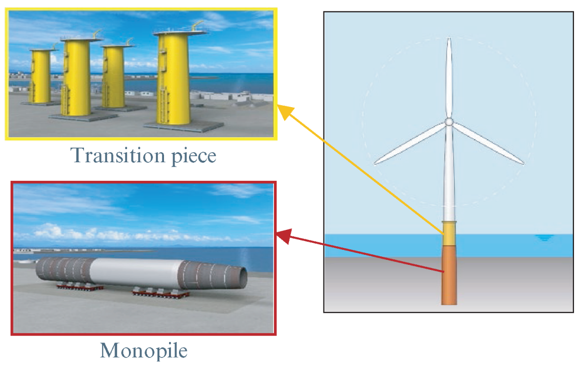


Fig. 5 Transition piece & monopile

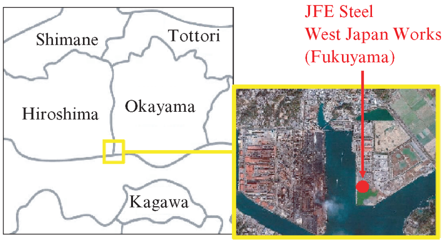


Fig. 6 New factory location map

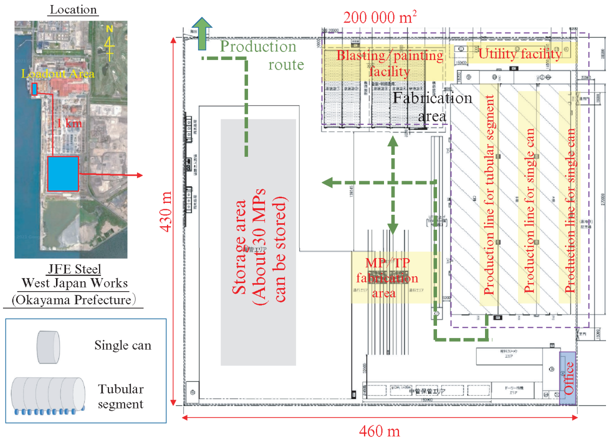


Fig. 7 Overview of new monopile factory

the storage area is inadequate, the storage yard of the Pipe Mill on the north side will be used temporarily.)

• Shipping quay: The shipping quay of the Pipe Mill will be used (quay water depth: 11 m)

3.3 Equipment Plan of New Factory

Figure 8 shows the flow of the monopile manufacturing process.

As the material, heavy and extra-thick steel plates manufactured by JFE Steel will be used. The weld volume (longitudinal joint, circumferential joint) will be reduced by using these large section, extra-heavy plates, and the preheat temperature for welding will be decreased by suppressing crack sensitivity. As a result, the manufacturing time will be shortened, and welding costs and generation of greenhouse gases (GHG) will be reduced. Warehouse management of the delivered plates will also be systematized so as to minimize plate restacking work in the new factory.

Fabrication of pipes will be carried out by the preceding plate joining method, in which a large plate is first fabricated by butt-welding the material plates, and roll bending is then performed in one operation. The strict dimensional accuracy requirements of the products are met by performing all plate dimensioning and beveling work by machining. Because it is necessary to consider shrinkage due to welding in the post-process and elongation caused by roll bending, dimensions will

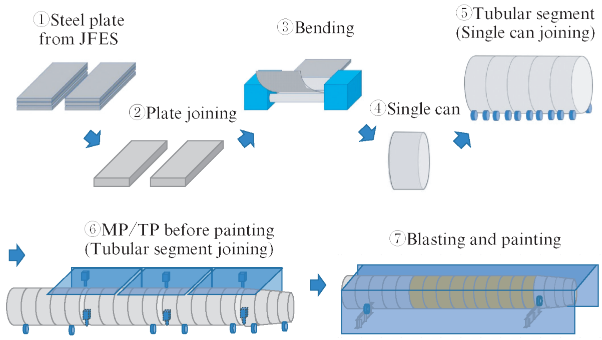


Fig. 8 Monopile manufacturing flow

be decided by utilizing accumulated data. The bending machine has a specification that enables edge bending, contributing to layout saving in the factory.

For welding of extra-thick plates (approx. t100 mm), JFE Engineering and JFE Steel jointly developed a high quality, high efficiency welding method, which was reflected in the welding equipment. As the welding method, multiple electrode submerged arc welding using a narrow bevel (bevel angle: 8 to 16°) has been adopted. The welding target position, which has a large influence on weld quality, is controlled by also using information from a laser sensor. The welding conditions (current, voltage, etc.) are controlled by digital data and fed back to quality management, etc. When welding the outer surfaces of butt welds and circumferential splices, the welding system is capable of welding multiple joints simultaneously, thereby shortening the manufacturing time.

Distortion (angular distortion) caused by welding of longitudinal splices is straightened by the bending machine, supporting strict dimensional accuracy (misalignment: 4 mm or less).

After finishing the weld bead in accordance with the design requirement, nondestructive testing of welds is performed by visual inspection, magnetic particle testing and ultrasonic testing. In ultrasonic testing, automatic ultrasonic testing is adopted to shorten the inspection time, reduce inspection costs and enable digitization of records. Moreover, since nondestructive inspections must generally be conducted 48 hours after welding, the factory layout was designed considering the timing and location of those inspections.

An anti-corrosion coating is normally applied to the inside and outside of products. The new factory has a climate-controlled indoor shop for blasting work (treatment of the substrate steel before coating the plate surface) and coating work, and work is possible under all weather conditions by using an air-conditioning system to control the temperature and humidity.

The equipment used for movement of products in the plant is also capable of responding to the increasingly larger size and weight of monopiles, as movement is performed by crane until the single can stage and by a self-propelled modular transporter from the tubular segment stage.

In carrying out the equipment planning, the following other points were also considered.

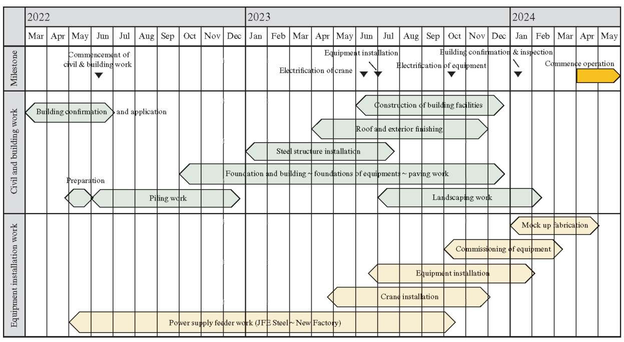
- Assuming the possibility of cases in which repair is necessary, disturbances in the production speed balance of the preceding and following processes, etc., a buffer area which does not stop the production line is secured.
- A backup system is provided for the unlikely event of equipment malfunction.
- A WiFi environment is introduced in the factory, making it possible to confirm the status of operations in real time.

3.4 Construction Schedule of New Factory

Discussions and procedures for obtaining various approvals for construction of the new factory began in July 2021, and construction at the site is scheduled to start upon approval of the building permit at the end of May 2022. The construction is broadly divided into civil and building construction, utilities (electricity, clean water, gas), installation of the crane and installation of the manufacturing equipment. Completion of the construction work by the end of December 2023 is targeted (**Table 2**).

A large amount of electric power will be consumed when using multiple welding machines, bending rollers and other equipment. Therefore, as part of the construction, a 22 kV power cable will be constructed from a substation located at the steel works 7.5 km from the new factory. Installation of the factory crane and construction of the power supply were completed in June 2022, and this crane is planned to be used in the installation of the production equipment. The construction of various construction buildings, equipment and product storage yards was performed based on the optimum foundation design in an effort to reduce the cost of building construction.

Table 2 New factory construction schedule



3.5 Reinforcement of Monopile Shipping Pier

Considering the upscaling of monopiles expected in the future, a roll-on type monopile shipping method was adopted, as there is a high possibility that the weight of the monopiles may exceed the crane capacity of heavy cargo carrier ships equipped with cranes as the size of monopiles increases.

On the other hand, although the shipping quay of the Fukuyama Pipe Mill will be used to ship monopiles, an attached barge was provided perpendicular to the south end of the shipping quay, as shown in **Fig. 9**, so as not to affect the welded pipe shipping work which is currently performed at the quay.

At this location, a temporary structure used exclusively for shipping monopiles is provided behind the mooring facilities and is connected to the above-mentioned barge via a rampway, so that the self-weight of the monopiles does not act on the existing mooring facilities (**Fig. 10**). In addition, because the neighboring shore protection work is a sloped embankment, the area where the monopiles travel on the land side is scheduled for ground reinforcement by installing piles or soil improvement.

3.6 Marine Transportation of Monopiles

Because monopiles are long, heavy structures, there are currently no transport vessels in Japan that can transport a large number of monopiles steadily by sea

Fig. 9 Monopile transport vessel mooring layout

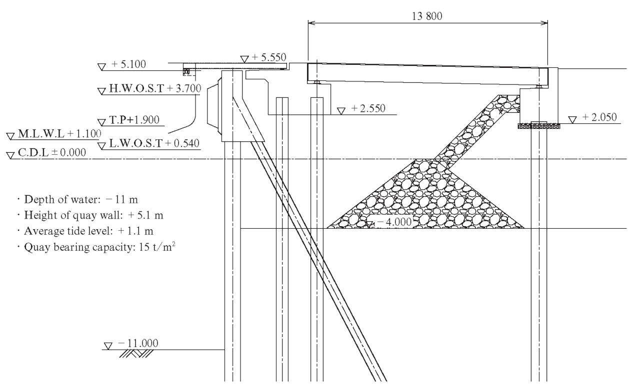


Fig. 10 Monopile shipping quay structure diagram

regardless of the season. Although the jurisdiction of marine transportation when actually implementing projects appears to differ in each project, it is extremely important, from the viewpoint of the business feasibility of monopile production, to secure transport vessels that are capable of steady marine transportation of large numbers of monopiles.

As a result of repeated feasibility studies and discussions with several marine shipping companies since last summer, JFE Engineering aims to secure multiple transport ships, and is currently conducting a detailed study of ballast equipment and transportation grillage that can support roll-on/roll-off handling of monopiles.

3.7 Toward Startup of the New Factory

Although JFE Engineering has an extensive track record in manufacturing offshore jackets for the oil and gas industries and pressure vessels, steel bridge piers and other structures that require welding of extra-thick steel plates, the manufacture of monopiles as foundations for offshore wind turbines is the company's first attempt in this field.

In order to be selected by project owners and EPC contractors in the future, we believe that it will be necessary to establish a manufacturing and quality management system, receive third-party technical due diligence in advance, and win the trust of clients. The following shows the specific response items and schedule (**Table 3**).

①Mock up test

- Identify the issues for upscaling by reduced scale testing (approx. φ4 to 5 m) (Tsu Works)
- Verify the manufacturing method at actual scale (approx. φ8 to 10 m) (new factory)

②Develop documented procedures for fabrication and quality management methods

Prepare written procedures conforming not only to Japanese standards but also DNV.

③Shipping and transportation plans

It will be necessary to prepare and receive examination by the Marine Warranty Survey for each construction project. However, as this is the first initiative of its type in Japan, JFE Engineering plans to receive advance examination by a third party based on a plan prepared for assumed conditions.

4. Conclusion

A conceptual drawing of the completed monopile factory is shown in **Fig. 11**. As offshore wind power generation enters the full-scale phase in the future, this technology will become one key type of energy infrastructure in Japan. By supplying the monopile foundations and jacket foundations that support the power generation equipment, JFE Engineering will accelerate the establishment of the national wind-turbine foundation manufacturing industry and contribute, at least in some small way, to realizing carbon neutrality in the future.

Table 3 Manufacturing and quality control system construction schedule

	FY 2021		FY 2022				FY 2023				FY 2024	
	3Q	4Q	1Q	2Q	3Q	4Q	1Q	2Q	3Q	4Q	1Q	2Q
Factory construction									Commissioning			
KASAOKA Factory	Planning		Procurement & construction								Operation	
TSU Works			Procurement & ground improvement					Operation				
Fabrication & quality management												
Mock up test	Element test					Certification of automatic UT				Mock up test		
Welding method			WPQT	WPS								
Fabrication method		Draft		Final								
Quality management method		Draft		Final								
Transportation plan	Shipping & stacking plan			Analysis of moored ship mortion			Submission of final report					
Confirmation by third party #												

#Third party: DNV or ClassNK etc.

Fig. 11 Conceptual drawing of monopile factory

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