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Seismic Design of Offshore Wind Turbine Withstands Great East Japan Earthquake and Tsunami

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Abstract: Japan's first open sea offshore wind farm, Kamisu offshore windfarm Phase 1, was stricken by an earthquake of intensity 6 on the Japanese seismic scale and a five-meter-high tsunami during the Great East Japan Earthquake on March 11, 2011. The wind farm resumed operation on March 14 after checks revealed no damage to the system, even though the wind farm was temporarily forced to stop due to the grid failure caused by the earthquake. Wind turbines require a precise seismic design especially in an earthquake-prone country such as Japan. Wind power Kamisu Phase 2 was built one year after the earthquake based on the experience of Kamisu Phase 1. This paper presents the seismic design of offshore wind turbines and the situation during the earthquake and tsunami.

Key words: Seismic, offshore wind turbine, Great East Japan Earthquake, tsunami.

1. Introduction

The design of wind turbines installed in an earthquake-prone country must take into account the loads imposed on the turbines due to ground shaking. There is no detailed design standard for earthquake resistance in the IEC (International Electrotechnical Commission) standard, IEC 61400-1. The Japanese government has stipulated some of the most rigorous earthquake building standards in the world, and wind turbines are required to comply with these standards. The standards define specific requirements in terms of earthquake motion, calculation of responses to earthquake ground motion, evaluation criteria, and so forth. This paper focuses on Japan's first open sea offshore wind farm, Wind Power Kamisu Phase 1, during the Great East Japan Earthquake and tsunami and the seismic design of Wind Power Kamisu Phase 2 based on earthquake experiences in Japan.

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2. Outline of the Wind Farm

2.1 Power Station Design

Wind Power Kamisu Phases 1 and 2 are both located offshore from Kamisu city in Ibaraki prefecture. The stations generate a total output of 30,000 kW (kilowatts) when the Hitachi wind turbines (HTW 2.0-80) are operating at their rated capacity of 2,000 kW. Each wind turbine stands around 60 m above the sea and has three 40-meter-long blades. Fig. 1 and Table 1 show an image and detailed specifications of the wind farm.

2.2 Windturbine Design

The nacelle (Fig. 2) contains the main shaft, gearbox, generator, and associated components. The nacelle bedplate has a girder structure. The gearbox is attached to the bedplate and transmits the torque from the main shaft to the generator. A roller bearing is used for the yaw system together with electrical actuators and a hydraulic brake system. The step-up transformer and

Fig. 1 Kamisu offshore wind farm.

Table 1 Outline of the wind farm.

Item	Description
Wind farm name	Kamisu offshore
Rotor	Downwind
Project status	Fully commissioned
Project capacity	30,000 kW
Turbine model (manufacturer)	HTW2.0-80 (Hitachi)
Turbine capacity	2,000 kW
Number of units	15
Total height/hub height	100 m/60 m
Rotor diameter	80 m
Offshore distance	Around 40 m
Sea depth	Around 5 m

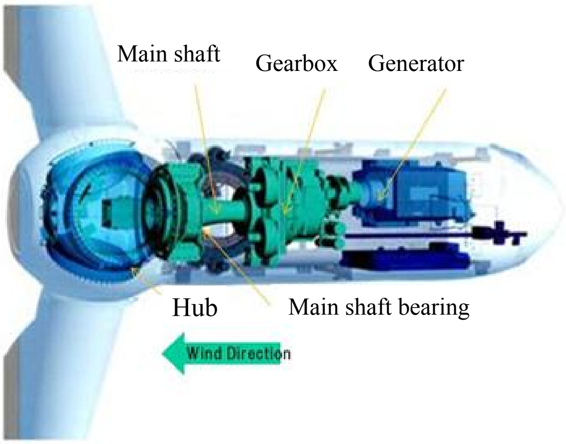


Fig. 2 Schematic of nacelle.

power conditioning system are not located in the nacelle (Fig. 3). This layout is designed to reduce the weight of the nacelle, lower the center of gravity, reduce seismic overturning moment and make these components more easily accessible. The converter and transformer are located at ground level to increase seismic resistance and facilitate maintenance.

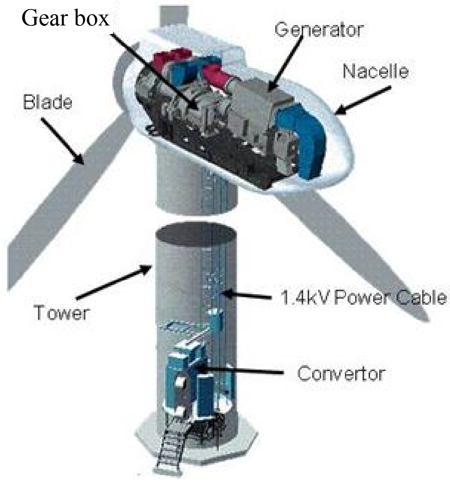


Fig. 3 Layout of major components.

2.3 Mono-pile Foundation

HTW2.0-80 turbines are installed at both Phases 1 and 2 of Kamisu Offshore Wind Farm. The turbine foundations are hollow cylindrical steel shells with 3.5-m outer diameter, embedded in concrete, and extend 17 m below the sea bed. The turbine towers are attached to the foundations with flange joints.

3. Influence of the Earthquake

Wind power Kamisu Phase 1 was stricken by an earthquake of intensity 6 [1] on the Japanese seismic scale (maximum acceleration of 422 cm/s^2 at Kashima city) (Fig. 4) and five-meter-high tsunami during the earthquake on March 11, 2011. The wind farm resumed operation on March 14, after checks showed no damage to the system, even though the wind farm was temporarily forced to stop due to the grid failure caused by the earthquake. During the four days without power, the wind turbines suffered minimal misalignment of the nacelles due to the inherent positive yaw characteristics of the downwind configuration (weathervane principle in standstill mode).

3.1 Tsunami Loads

In the seismic analysis for Kamisu Phase 2, the seismic loads at Kamisu Phase 1 during the earthquake were taken into consideration. A tsunami height of 5.7 m and wave speed of 8.5 m/s were set based on

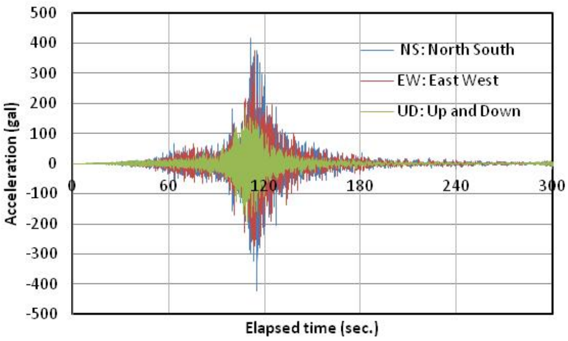


Fig. 4 Earthquake waveform [1] at Kashima city, Ibaraki.

estimated and measured values during the earthquake. The Kamisu site has typically geometrical conditions for offshore wind turbines, including a straight coastline and shallow water, but these amplify the height and speed of a tsunami.

Because a tsunami has a very long period, it can be assumed as a surge of water. According to "Technical Standards and Commentaries for Port and Harbour Facilities in Japan" [2], tsunami speed "*C*" was calculated. Tsunami wave kinetics parameters were defined by Morison's Eq. (1) [3]. Tsunami force "*U*" was calculated by Eq. (2).

$$F = \frac{1}{2} C_D \rho_W A u|u| + C_M \rho_W V_{\dot{u}} \quad (1)$$

$$U = \frac{C\eta}{h} = \eta \sqrt{\frac{g}{h}} \quad (2)$$

where,

η: sea level variation from normal tidal level by tsunami (5.7 m);

C: tsunami velocity (8.4 m/s);

h: depth of water (4.5 m);

g: gravitational acceleration (m/s^2).

The loads used in these calculations are listed in Table 2. The tsunami load is 40% bigger than the wave load. Mono-piles may have an advantage of reducing the tsunami load and wave load as shown in Fig. 5 and Table 3. The situation of "Tsunami + power production wind" is much less severe than "extreme wave + extreme wind". The situation of "extreme wave + extreme wind" is used for the following stress assessment.

3.2 Synthetic Earthquake Waves

In time history analysis, seismic loads acting on a wind turbine are estimated by introducing synthetic earthquake waves at the tower base.

The ground motion response spectra at the ground surface were given by a simplified method considering inelastic amplification characteristics of the surface layers, which amplify the waves. The methodology shown in Fig. 6 follows the guidelines of the Japanese Ministry of Construction.

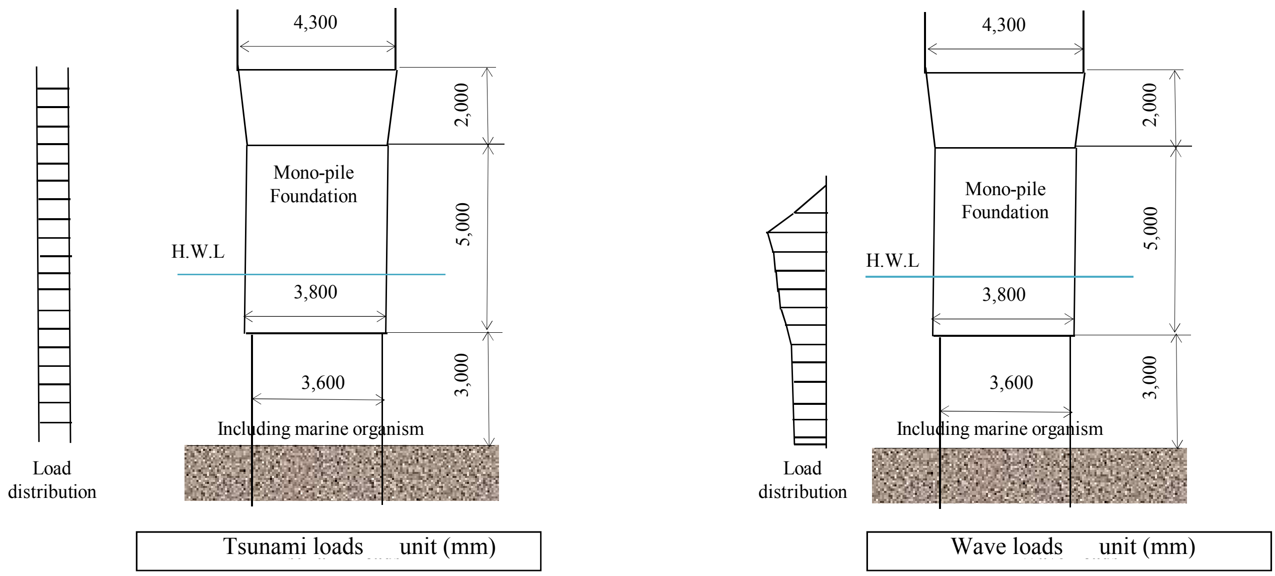


Fig. 5 Comparison between tsunami and wave load.

Table 2 Overturning moment at bottom of tower.

Situation	Depth	Tsunami height	Wave load	Locus section	Moment
Tsunami	4.5 m	5.7 m	1,408 kN	2.22 m	7,350 kN-m

Situation	Depth	Wave height	Wave load	Locus action	Moment
Extreme wave	4.5 m	4.83 m (period 13.2 sec)	1,163 kN	1.51 m	5,248 kN-m

Table 3 Load assumptions (unit: kN-m).

Situation	Wave	Wind	Total
Tsunami + power production wind	7,350	18,892	26,242
Extreme wave + extreme wind	5,248	63,570	68,818

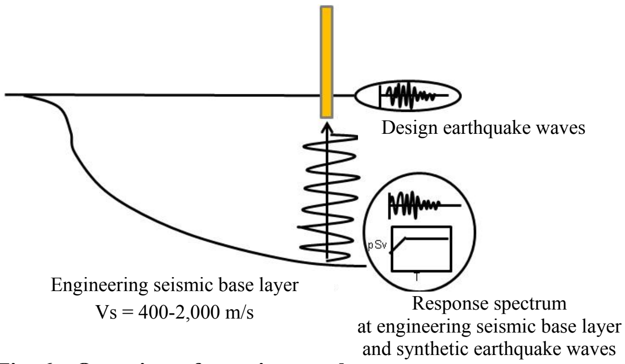


Fig. 6 Overview of creating synthetic waves.

3.3 Analysis Method and Model

The dynamic response of the Kamisu Phase 2 turbines is analyzed using a spring mass model with 30 nodes (Fig. 7) with simulated seismic waves. The analysis methodology reflects the experience at Kamisu Phase 1 during the earthquake. The analysis of the tsunami load was added to the Kamisu Phase 1 analysis. The detailed evaluation process complied with the GL (guideline) [4], Japanese Building Code and Japanese Electric Utility Industry Law. Many parameters were evaluated to clarify the response of the turbines to possible load combinations by conducting analyses using a turbine-specific code, the BLADED code, and finite element method code (Dynamic PRO of Union System Inc.). The loads listed in Table 4 were used for these analyses.

4. Analysis Results

4.1 Displacements and Accelerations

The maximum displacements were 435 mm (L1 earthquake) and 871 mm (L2 earthquake) at node 30 (68.69-m height), as shown in Fig. 8. The shape of the displacement distribution is similar to the 1st mode of the natural frequency, period of vibration = 2.4 sec. The period of the seismic vibration is more than 0.1 sec. The excitation period of the wind turbine rotor is 1.14 sec. The period of the natural frequency approximately matches the dominant frequency of the earthquake. Lowering the height of the center of gravity controls the natural frequency of the wind

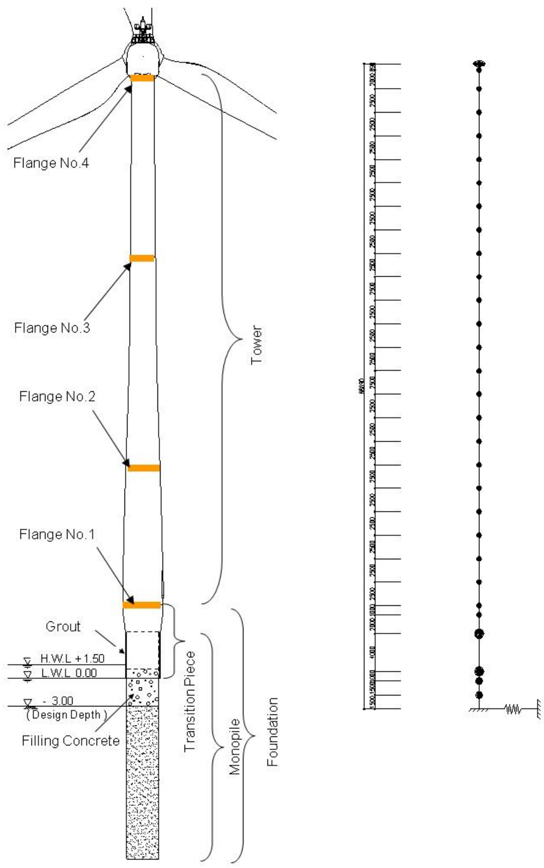
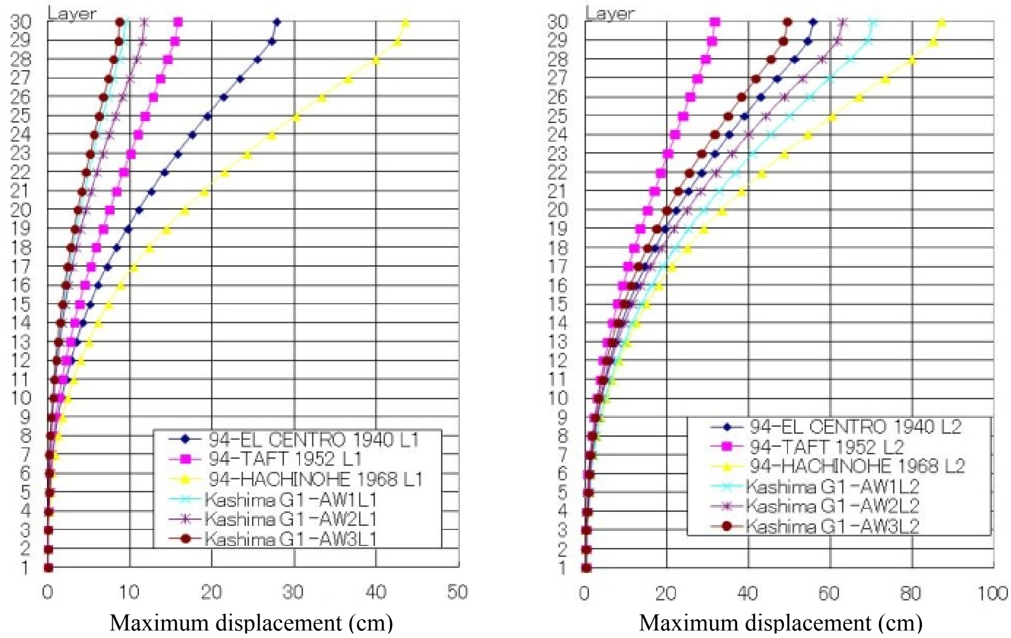


Fig. 7 Turbine and analysis model.



(a) L1 (b) L2

Fig. 8 Maximum displacement.

Table 4 Design load cases.

Condition	Situation	G	P	R	FL	K1	K2	KV
Temporary	L1	Y	Y	Y	Y	Y	-	Y
Extreme	L2	Y	Y	Y	Y	-	Y	Y

G: gravitational loads; P: payloads; R: load at annual average wind speed; FL: wave load at high tide; K1: seismic loads at L1 earthquake; K2: seismic loads at L2 earthquake; KV: vertical.

turbine, such that it does not resonate with modes higher than the first one.

4.2 Bending Moment

The maximum moments in the turbine segment were 29.0 MN-m (L1 earthquake) and 58.1 MN-m (L2 earthquake) at node 1 at 0.15-m height, as shown in Fig. 9. Both moments were less than the allowable levels. The design criteria, allowable temporary bending moment and L2 were defined by calculation using the polar moment of inertia of area and factor of stress concentration.

5. Conclusions

The experience during the Great East Japan Earthquake confirmed that the configuration of the HTW2.0-80 turbine with mono-pile foundation had

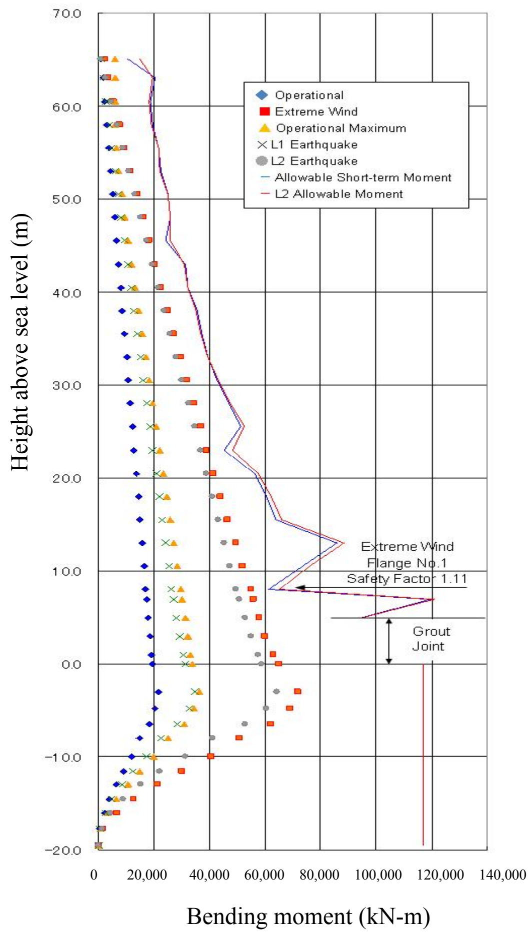


Fig. 9 Bending moment distribution.

sufficient durability to withstand seismic vibration and tsunami. The extreme wind load was greater than the tsunami load at the mono-pile level during the earthquake in 2011. A model of the HTW2.0-80 turbine with mono-pile foundation was built. Using this model and the dynamic PRO code, a series of simulations was conducted to investigate earthquake and tsunami phenomena. The seismic resistance design will continue to be modified for various site conditions and foundation types.

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