METOCEAN DESIGN CONDITION FOR “FUKUSHIMA FORWARD” PROJECT

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Metocean condition for the Fukushima FORWARD project is presented. Wind speeds and tsunami are predicted by Monte Carlo simulation and Tsunami simulation, respectively. For wave condition, extreme sea state and normal sea state are evaluated by published data and newly proposed wind-wave and swell combination formula, respectively. Surface current and water level are evaluated by extreme value analyses of hindcast simulation and historical data, respectively.

Keywords: floating wind turbine, design conditions, Monte Carlo simulation, extreme value, tsunami

INTRODUCTION

For the revitalization in Fukushima prefecture from disasters by the Tohoku region Pacific coast earthquake and accident of Fukushima Daiichi nuclear power plant in 2011, Japanese government initiated the world first *Floating OffshRe Wind fARm Demonstration* project (FORWARD project). In this paper, results of assessment on metocean conditions for 2MW floating wind turbine and the world first floating substation are presented for wind speed, water level, wave, current and tsunami.

LOCATION OF THE *FORWARD* PROJECT

Site of the FORWARD project is located 20km offshore of the east coast of Fukushima prefecture where sea depth is approximately 120m.

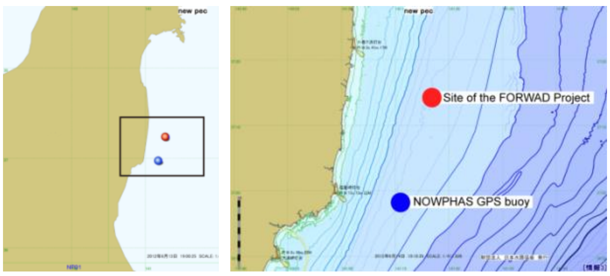

Fig. 1. Location of the FORWARD project.

METEOCEAN CONDITIONS

Wind speed, water level, wave, surface current and tsunami for design condition are assessed below by means of simulations and measurements.

Wind speeds

In the mixed climate like Japan, it is important to taken into account both of wind climates, i.e. tropical and the extratropical cyclones when estimating extreme wind. Therefore, in this study, 50 year extreme wind speed was evaluated by synthesizing probabilities of non-exceedance of two independent processes, i.e. typhoon $F_T(u)$ and extratropical cyclone $F_E(u)$ by Eq.(1) [1]. Figure 2 shows the synthesis of the probability distributions of annual maximum wind speeds by tropical and extratropical cyclone, where probabilities of non-exceedance of the annual maximum wind speed was calculated by Monte Carlo simulation of 10000 years for tropical cyclone and method by Gomes and Vickery(1977)[2] for extratropical cyclone based on data obtained by converting 2 year data observed at nearby gas field to the hub height. 50 year extreme wind speed at hub height of 60m was estimated as 48.3 m/s.

$$F_M(u) = F_E(u) \times F_T(u) \tag{1}$$

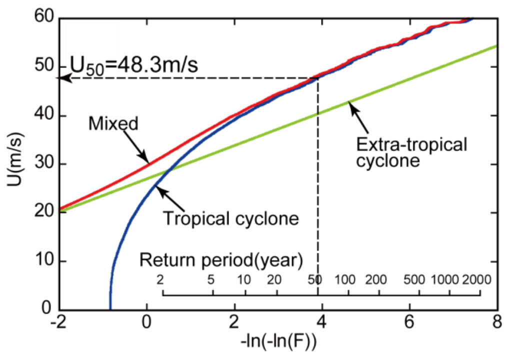

Fig. 2. 50 year extreme wind speed.

Accumulation time for the assessment of fatigue was also evaluated by combining the two frequencies of wind, i.e. typhoon wind and non-typhoon wind. Mixed frequency distribution was estimated by assuming that they can be approximated by the Weibull distribution, where k=1.99 and c=15.27m/s for typhoon wind and k=1.73 and c=8.06m/s for non-typhoon wind. Figure 3 shows the Annual accumulation times for each wind speed.

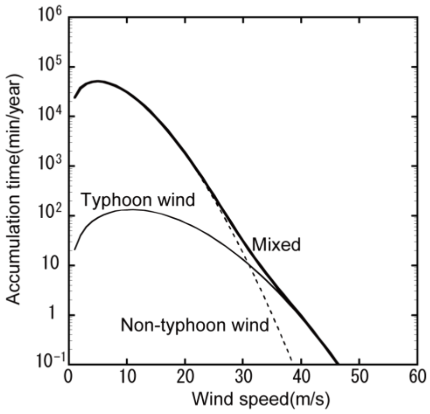

Fig. 3. Annual accumulation times.

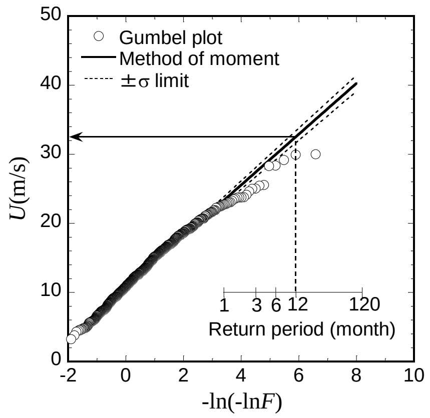

Fig. 4. Extreme value analysis for 1 year extreme wind speed.

1 year recurrence wind speed was estimated by the extreme value analysis based on the gas field data. U_1=32.5m/s was obtained by the method of moment with uncertainty of 3%. Because $U_1/U_{50}=0.67 < 0.8$, an estimate of 38.6 m/s by IEC61400-1 Ed.3 was confirmed to be conservative. Power law exponent of vertical profile was estimated by 3D analysis as 0.1 which is as same as 0.11 by IEC61400-3. For the reference turbulence intensity, 0.12 by IEC61400-3 was used. Since nearby observation was lower than it, it will be a conservative estimate. For power generation and fatigue, $I_{90}=\sigma_1/U_{hub}$, $\sigma_1 = I_{ref}(0.75U_{hub}+5.6)$ and α=0.14 was used.

Water level

Highest High Water Level was obtained by combining the astronomical with the meteorological tide. According to IEC61400-3, Highest Astronomical Tide (H.A.T.) is used for astronomical tide, however, in Japan High Water Level (H.W.L.) has been commonly used [3]. Therefore, here, according to [3], H.H.W.L. was estimated by adding meteorological tide which is a 50 year return period of typhoon sea level departure from normal to H.W.L.

For astronomical Tide, Onahama data was used as M.S.L.=C.D.L.+0.84m and H.W.L.=C.D.L.+1.44m.

For meteorological tide, 50 year typhoon sea level departure from normal was estimated by the Eq.(2),

$$\zeta = a\Delta p_{50} + bU_{10}^2 \cos\theta + c \tag{2}$$

where a, b, c and θ are empirical constants provided by [3], U_{10} is a 50 year 10 min. wind speed at 10m above mean sea level and Δp_{50} is a 50 year value of the central pressure depression. U_{10} was calculated from hub height wind speed of 48.3m/s, which was obtained by Monte Carlo simulation, with power law exponent α=0.1. θ is an angle to the wind of U_{10}, and was set as zero for a conservative estimate of ζ.

Δp_{50} was determined by extrapolation of extreme value analysis of pressure depression data which is defined as difference between ambient pressure and central pressure for typhoons which passed through an area within 500km of radius from the site and whose central pressure was less than 985 hPa in 47 years from 1961 to 2007. Figure 4 shows a log-normal approximation of Δp_{50}.

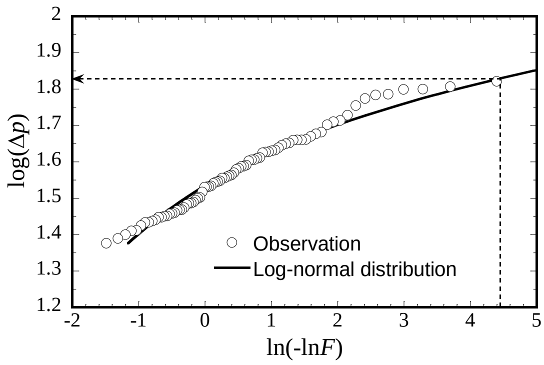

Fig. 5. Probability distribution of the central pressure depression for a use in the prediction of the meteorological tide in the highest high water level.

Non-exceedance probability of 50 year is calculated as $F = 1 - 1/(\lambda R)$, where λ is average occurrence per year=N/K, N is a number of typhoon, K is an observation period. Since N=81 for the site, λ=1.7234, F=0.988395 and Δp_{50}=67.5hPa. In Table 1, two meteorological sites nearest adjacent to Onahama, i.e. Chosi and Miyako, were compared and conservative vale of C.D.L.+2.77m at Choshi was adopted as the highest high water level of the site.

Table 1. Water level.

Parameters	Choshi a=0.622 b=0.056 c=0	Miyako a=1.193 b=0.012 c=0
U_{10min} (m/s)	40.4	
Δp (hPa)	67.5	
ζ(m)	1.33	1.00
H.W.L.(m)	C.D.L.+1.44	
H.H.W.L.(m)	C.D.L.+2.77	C.D.L.+2.44
	C.D.L.+2.77	

Wave height and wave period

Extreme sea state was evaluated based on the published data in Table 2. From the table, 11.71m was adopted for 50 year extreme wave height and 13s are combined to determine the extreme sea state.

Table 2. Published extreme sea state.

Sources of published data		Wave height(m)	Wave period(s)
NILIM[4]	Tomioka	11.71(ALL)	-
	Fukushima	11.0(ENE-ESE)	13
Fukushima prefecture civil engineering design manual(2008)		8.4(E-SE)	13
INPEX gas field design value		20/1.86=10.8	12

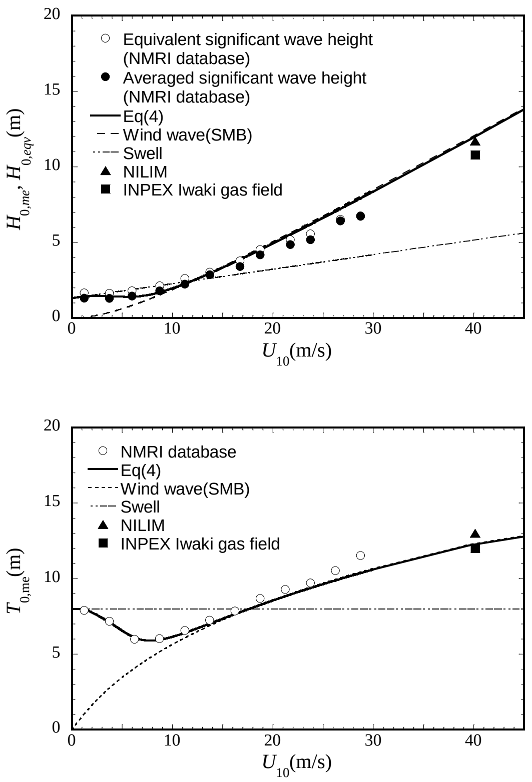

Fig. 6. Wave height and wave period for normal sea state where swell is combined with wind-wave.

In the normal sea state, wave height and wave period were estimated by weighting average of wind-wave and swell empirically as follows,

$$
\begin{aligned}
H_0 &= \alpha H_{0,\mathrm{SMB}} + (1-\alpha) H_{0,\mathrm{swell}} \\
T_0 &= \alpha T_{0,\mathrm{SMB}} + (1-\alpha) T_{0,\mathrm{swell}}
\end{aligned}
\tag{3}
$$

where subscripts “SMB” and “swell” indicates estimates of significant wave height and corresponding wave period by SMB method and swell respectively and α is their weighting function which are obtained as follows,

$$
\begin{aligned}
H_{0,\mathrm{SMB}} &= \frac{0.3U_{10}^2}{g}\left[1-\left(1+0.004\sqrt[2]{235000gU_{10}^{-2}}\right)^{-2}\right] \\
T_{0,\mathrm{SMB}} &= \frac{1.37\cdot 2\pi U_{10}}{g}\left[1-\left(1+0.008\sqrt[3]{235000gU_{10}^{-2}}\right)^{-5}\right] \\
H_{0,\mathrm{swell}} &= 1.31+(2.46-1.31)U_{10}/12, \quad T_{0,\mathrm{swell}} = 8 \\
\alpha &= \max\left(0.4\tan^{-1}(0.34U_{10}-1.88)+0.39, 0\right)
\end{aligned}
\tag{4}
$$

Figure 6 shows comparisons between Eq.(4) and following defined mean and equivalent significant wave heights and harmonic mean wave period which are obtained based on NMRI database [5] of this area. Wave height and period in the low wind speed region are successfully represented by this proposed model.

$$
H_{0,eqv} = \sqrt[m]{\frac{1}{n}\sum_{i=1}^{n} H_{0,i}^{m}} \quad (m=4), \quad H_{0,me} = \frac{1}{n}\sum_{i=1}^{n} H_{0,i}, \quad
T_{0,me} = n \Big/ \sum_{i=1}^{n} \frac{1}{T_{0,i}}
\tag{5}
$$

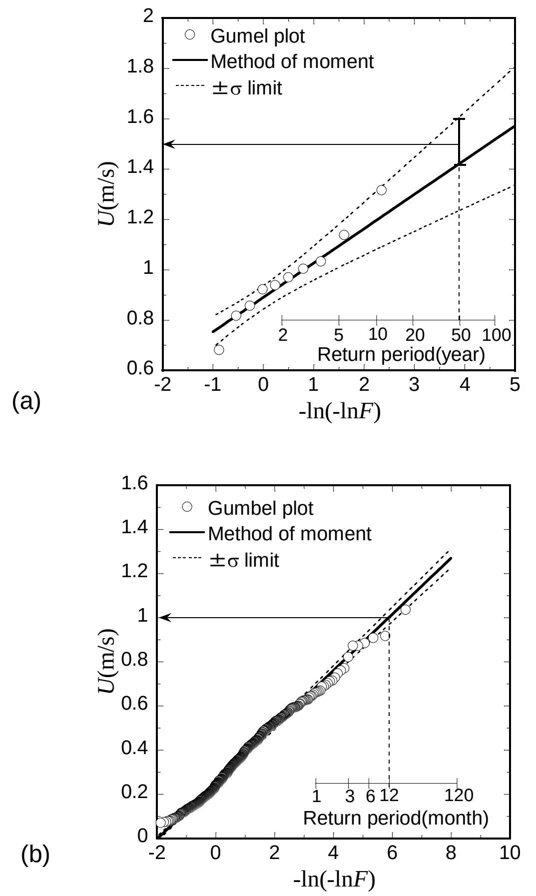

Fig. 7. Extreme value analyses of surface current for 50 year(a) and 1 year recurrence(b).

Surface current

Figure 7 shows 50 year and 1 year recurrence values of surface current which were evaluated by extreme value analyses of hindcast data by JCOPE [6]. Since the total number of annual maximum data is limited to ten, its uncertainty of 13.5% is too large to neglect. Therefore extreme 50 year value was determined by adding half of the standard deviation to the value which was obtained by the method of moment as 1.5m/s. On the other hand, there is little uncertainty in an extreme value distribution based on daily maximum data, 1 year value is obtained straightforward from the method of moment as 1.0m/s.

Tsunami

Tsunami was simulated by solving nonlinear shallow water long wave equations numerically, see Fig.8. The fault was modeled by Mansinha and Smylie model [7] which was combined with fault parameters by Imamura et al. [8]. The simulation was validated by wave measurements by a NOWPHAS GPS buoy [9] near the site. In Fig.9, estimated maximum peak water level and corresponding horizontal velocity are 3.2m and 0.77m/s, which is slightly smaller than a value estimated by the linear long wave theory of 0.88 m/s in which convection and friction are not considered. Annual mean surface current of 0.1m/s [10] was added to the former value to determine the design value.

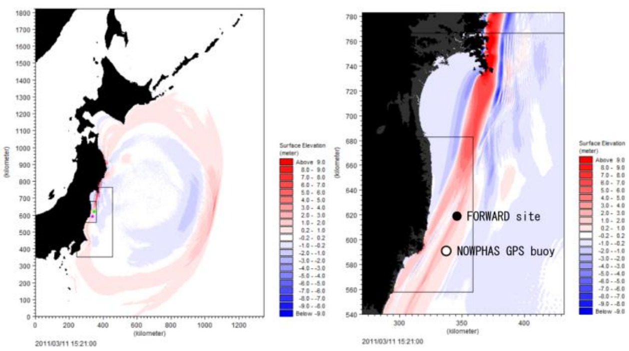

Fig. 8. Tsunami simulation for the 2011 Off the Pacific Coast of Tohoku Earthquake. Water levels in the figure are at the moment of site maximum.

CONCLUSION

Metocean condition for a 2MW floating wind turbine and a substation of the Fukushima FORWARD project was presented. It is worthy to note that the world first floating metocean observation was started its operation in December 2013 by which the prediction methodology will be validated.

ACKNOWLEDGMENT

This study was accomplished in the Fukushima floating offshore wind farm demonstration project which is financially supported by the Ministry of Economy, Trade and Industry. The authors would like to thank to Masao Komatsu of Mitsubishi Heavy Industry and Yuji Awashima of Japan Marine United for their cooperation to this study.

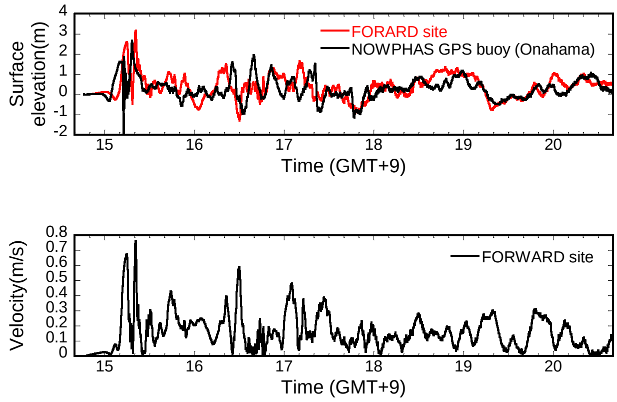

Fig. 9. Tsunami surface elevation and absolute velocity.

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