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Probabilistic analysis of Monopile supporting Offshore Wind Turbine considering joint probability of wind and waves

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SUMMARY
The design of offshore wind turbine (OWT) monopile foundations requires a realistic representation of the combined wind and wave loading. Conventional fully correlated approaches, which combine independent extreme values of environment variables, are conservative and often overlook their stochastic dependence. In this study, a joint probabilistic model is developed using long-term wind and wave data, where wind speed is modelled marginally, and wave parameters are represented by conditional distributions. Monte Carlo Simulation (MCS) framework is employed to propagate environmental uncertainties through monopile response analysis. Representative sea states are sampled from the joint distribution, and the corresponding loads are applied to a finite element model to evaluate the Serviceability Limit State (SLS) performance in terms of annual probability of failure. The study shows that the joint probability-based approach provides a more realistic and reliable OWT foundation response.

Keywords: offshore wind turbine, Joint probability, Limit state, Finite element model.

1. INTRODUCTION

Monopile foundations are widely adopted for offshore wind turbines (OWTs) due to their ease of installation and lower cost (Wu et al., 2019). Their design is strongly affected by environmental loads arising from wind and wave interactions. Traditional design practices used in (Arany et al., 2017; Jana et al., 2024) assumes full correlation between wind and waves, oversimplifying the loads. In general, there is a positive correlation between wind and wave parameters, and the relationship is neither linear nor fully synchronized (Zhang et al., 2023). Consequently, for a given wind speed, a range of wave heights may exist, showing the probabilistic nature.

Recent advances in offshore engineering emphasize probabilistic approaches to measure the safety of structures (DNV, 2016; Haldar et al., 2018). The joint probability model captures a range of environmental states, each with different likelihoods of occurrence. The probability of failure can then be estimated from the structural response to the corresponding loads by integrating the likelihood of limit state exceedance (Wang et al., 2022).

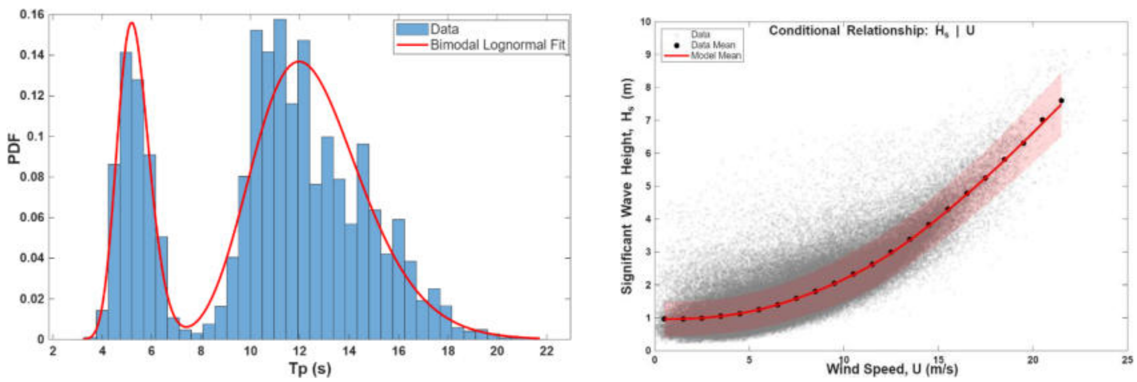
The current study develops a joint distribution of wind and wave parameters using a conditional probability framework based on a 20-year hourly (ERA5) dataset for a FOWIND site located along the Tamil Nadu coast, India (FOWIND, 2018) . Monte Carlo Sampling is employed to sample sea states from the joint model, and the corresponding loads are calculated. A finite element model (FEM) is used to evaluate the monopile response and the annual probability of failure is computed based on the Serviceability Limit State (SLS).

2. METHODOLOGY

2.1. Joint Probability Model

A probabilistic framework is developed, with wind speed (U) characterized by a marginal Weibull distribution, and significant wave height (Hs) is conditioned on wind speed using 1m/s bins, using a lognormal distribution. Subsequently, the peak spectral period (T_p) is conditioned on Hs by discretizing it into 0.5m bins using a bimodal lognormal distribution to account for sea swell and wind waves, as presented in Figure 1(a). This conditional modelling is consistent with (IEC, 2019). Goodness of fit tests were performed to choose the best fits and finally the joint probability is defined as in Eq (1), where *f*() represents the probability density function.

$$f(U, Hs, Tp) = f(U)f(Hs|U)f(Tp|Hs) \quad (1)$$

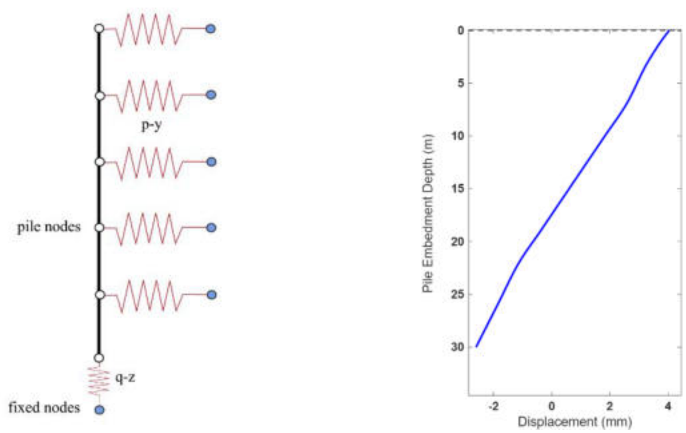


(a) **(b)**

Figure 1. (a) Marginal bimodal lognormal distribution of T_P (b) Conditional Mean of $f(H_s|U)$

2.2 Numerical Model

A 1-D non-linear FE model of NREL 5MW OWT is developed in OpenSees (McKenna et al., 2011). The monopile is modelled using the beam on nonlinear Winkler foundation (BNWF) approach, and the soil-structure interaction (SSI) is represented by p-y curves as depicted in Figure 2(a). The soil data is obtained from (FOWIND, 2018) report. Wind loads include rotor thrust and tower drag force and wave load is calculated using Morison's equation (Morison et al., 1950) accounting for both drag and inertia components. The loads are combined to compute the resulting mudline bending moment, which serves as the input to the numerical model.



(a) **(b)**

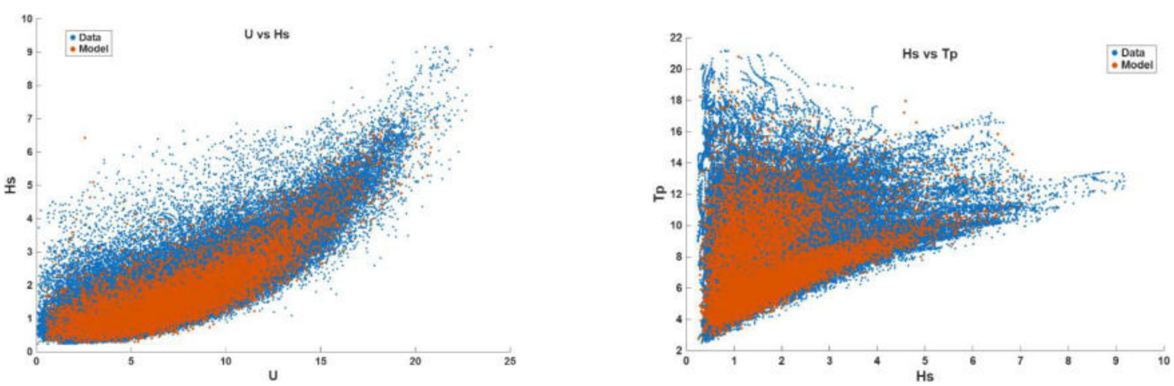
Figure 2. **(a)** Schematic representation of the numerical model of the monopile foundation. **(b)** Displacement v/s embedment depth for ULS scenario

2.3 Performance Assessment

Representative sea state samples are obtained from the joint probability model using MCS. For each sampled sea state monopile response is computed using numerical model. The annual probability of failure is then evaluated following the Serviceability Limit State based on the allowable mudline deflection of 0.5° (DNV, 2016; IEC, 2019)

3. RESULTS AND DISCUSSIONS

The accuracy of the joint model is validated, as inferred from Figure 1(b), the conditional mean of $f(H_s|U)$ agrees well with the empirical mean, indicating the model accurately captures the dependence behaviour. Similar checks are done for $f(T_p|H_s)$. From this conditional joint model 5000 sea states are sampled, the resulting scatter plots shown in Figure 2 demonstrate good agreement with the model and the sampled points covering a wide sea state. The model successfully reproduces the underlying correlation and variability as seen in Table 1.



(a) **(b)**

Figure 3. Scatter plot comparison for conditional estimates of raw data and sampled points through MCS **(a)** $f(H_s|U)$ **(b)** $f(T_p|H_s)$

Table 1. Correlation result comparison

Correlation	Data	Model
f(Hs|U)	0.811	0.823
f(Tp|Hs)	0.363	0.355

Table 2. Load Calculation for Ultimate Limit State (ULS)

Load	Value	Input Parameters
Rotor Thrust	1.24 MN	Maximum water depth = 20m (FOWIND, 2018)
Tower Drag	0.14 MN	Density of air = 1.225kg/m^3
Total wave load	2.75 MN	Density of water = 1030 kg/m^3
		Thrust Coefficient = 0.14 (Arany et al., 2017)
		Drag Coefficient (wind) = 0.5 (DNV, 2016)
		Drag Coefficient (wave) = 1.2 (Haldar et al., 2018)
Total Mudline Bending Moment	184.63 MN-m	

First, the monopile response under ULS (Ultimate Limit State) is assessed. The 50-year sea state given by $[U_{50}, H_s|U_{50}, T_p|(H_s|U_{50})$ is estimated from the conditional joint probability model, and

the corresponding loads are summarized in Table 2. Figure 2(b) demonstrates satisfactory performance of the monopile foundation in terms of pile displacement under ULS.
For SLS, the response of the monopile is evaluated for each sea state, the failure is defined when the response exceeds the allowable limit. The probability of failure is then estimated as the ratio of the number of exceedances to the total number of simulated cases.

4. CONCLUSIONS

The study demonstrates that the proposed joint probability model effectively captures environmental variability and provides a realistic representation of the sea states. By capturing the dependencies among the environment variables (U, H_s, T_p), the approach ensures greater accuracy in load calculation than simplified methods, thereby avoiding conservatism.

The integration of MCS further enables robust estimation of serviceability performance. The study contributes to risk-based design practices for offshore wind foundations. By linking a probabilistic environment model with structural performance, the framework enhances confidence in safety evaluations.

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