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# Seismic Design of Large Offshore Wind Turbine Considering Rocking Vibration

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**Abstract.** Offshore wind turbines (OWT) are gaining popularity due to the generation of a reliable quantity of renewable energy. Jacket structures are generally used to support the large OWT structures at a water depth of 50-70 m. Offshore wind turbine structures are generally designed as a soft-stiff approach, where the fundamental frequency of OWT structure lies between the rotor frequency (1P) and blade passing frequency (3P). The first mode of vibration of jacket supported OWT structure is most likely to be the rocking mode of vibration due to the relatively lower vertical stiffness of shallow foundations. The natural frequency due to rocking modes of vibration may close to the 1P and wave frequency, which may cause resonance of the OWT structure. This study investigates the effect of both operational and seismic load considering horizontal and vertical seismic motions on the dynamic response of a four-legged jacket supported OWT structure on a pile, installed in a layered sand deposit. A three-dimensional finite element model of the soil-pile-jacket-tower is developed in ABAQUS. A parametric study is carried out to examine the amplification of response at the tower and maximum mudline rotation of monopile due to various aspect ratios of jacket and embedment of the pile.

**Keywords:** Jacket foundation, offshore wind turbine, rocking motion, multidirectional motion.

## 1 Introduction

During the early days, there was not much interest in the use of renewable energy sources, but due to the increase in demand, environmental pollution, and non-availability of resources makes the human focus more on wind energy as an alternate source to meet future needs. According to the reports of the Global Wind Energy Council, 60.4 GW of new installations brings global cumulative wind power capacity up to 651 GW in the year 2019, and 355 GW of new capacity will be added between 2020-2024, that is nearly 71 GW of new installations each year until 2024 [1]. In order to achieve this global demand, researches are now focused on deeper water, and most of these are seismically active zones. Jacket structures are mainly used to support large wind turbines in deeper waters. Jackets are three or four-legged structures supported on either deep foundations (piles) or shallow foundations (suction caissons). The height of the jackets generally varies between 50-70 m, which may vary depending upon the depth of the water depth and the wave height.

The design of the jacket supported offshore wind turbine (OWT); the first eigenfrequency of the structure should not coincide with the natural frequency of rotor or wave, which may, in turn, leads to resonance and affects the fatigue performance of the structure. In order to avoid this, there are three design approaches (a) soft-stiff range: it implies that the structure is too flexible and also wave frequency may lie in this range, which may lead to resonance, (b) stiff-stiff range: This range is economically unfeasible as it leads to a too rigid structure, and (c) soft-stiff range: the natural frequency lies between 1P and 3P range. This is the optimum range for the best design. [2]. Because of this reason, most of the design will be limited to the soft-stiff range. It has been observed through scaled model tests that the first eigenfrequency of vibration for jacket supported OWTs corresponds to low-frequency rocking modes of vibration, and this vibration corresponds to a frequency that is close to the 1P (rotor) frequency range and wave frequency. It may cause resonance and fatigue damage of the OWT structure. The main parameters which influence the mode of vibrations are the ratio of superstructure stiffness to vertical stiffness ratio of the foundation and the aspect ratio of the jacket [3,4]. Depending on these parameters mentioned above, two modes of vibration can happen in Jacket Supported OWT that is Sway or rocking mode of vibration. If the vertical stiffness of the foundation is low than that of the stiffness of the superstructure, the rocking mode of vibration may be a fundamental mode of vibration. As the vertical stiffness of the foundation increases, the vibration mode moves to sway-bending, and the corresponding first natural frequency increases and approaches the fixed base natural frequency [3].

For the satisfactory performance of OWT, the maximum allowable permanent tilt of the structure specified by the wind turbine manufacturers is 0.75 degrees, and the allowable installation allowance is 0.25 degrees, and therefore, the maximum allowable permanent tilt is about 0.5 degree [5]. This study examines the response of pile and tower when it is subjected to multidirectional seismic excitation in addition to operational loads. The effect of the aspect ratio of jacket structure and pile length on the maximum mudline rotation of monopile is studied. The 3D numerical model is developed in a commercial software ABAQUS. The soil domain and pile are considered as three-dimensional continua. The superstructure is modeled using the Euler-Bernoulli beam.

The present study examines the variation of the natural frequency for jacket structure supported offshore wind turbines for various embedment lengths of the pile by considering 3D soil pile structure interaction. A parametric study is conducted by varying the aspect ratios of a jacket and embedded length of the pile to examine the responses of the structure subjected to seismic loading and other operational loads.

## 2 Model Description

The jacket supported offshore wind turbine is modelled in ABAQUS CAE. The jacket and tower are modelled using beam elements, and the pile is modelled as a solid element. The rotor-nacelle-assembly mass is considered to lumped at tower top. The nonlinear behavior of soil is represented by using Mohr-Coulomb Plasticity. The properties of soil and the dimensions of OWT are selected from the literature [6]. Fig. 1. shows the schematic diagram of the offshore wind turbine supported by jacket structure, where $L_p$ is the embedment length of the pile, and $L_B$ is the base width of jacket. The height of the rotor above mudline ($h$) is 157.63 m, the tower height ($h_t$) is 89.63 m, and the detailed geometric descriptions are given in Table 1. Based on a convergence study, the dimension of the soil domain is considered as 150 m × 150 m × 90 m depth. The jacket bottom and pile heads are connected with tie constraints. Initially, gravity analysis is conducted to simulate in-situ stress conditions. The bottom plane of the soil domain is considered as restrained in all directions, and roller boundary condition is applied at the lateral boundaries of the soil domain during the gravity analysis. Subsequently, constraints in all three directions are released at the bottom plane of the soil domain to apply the seismic acceleration. Three components of seismic motion, namely two in orthogonal and vertical components, are applied for this study. The operational loads, namely, wind thrust, 1P load, 3P load, tower drag, and wave load, are applied. The gravity analysis is conducted using a quasi-static solver. The dynamic analysis is carried out using a transient fidelity solver in ABAQUS. The eigenfrequencies of the OWT is determined using the *Linear Perturbation step* and Lanczos solver. A schematic diagram of the FE model is shown in Fig. 1.

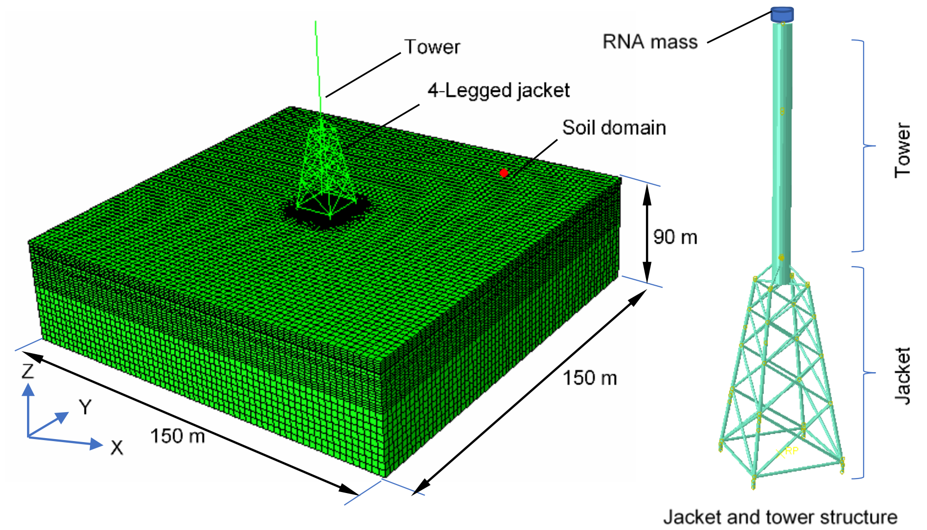


**Fig. 1.** 3D numerical model of jacket supporting 10 MW wind turbine.

## 2.1 Reference Wind Turbine

A 10 MW reference wind turbine data is obtained from the literature [7]. The jacket structure of the 10 MW turbine is obtained from Von Borstel [6]. The rotor frequency (1P) of 10 MW turbine vary from 0.1 – 0.16 Hz, and the 3P frequency is between 0.3 – 0.48 Hz. The properties of DTU 10 MW are given in Table 1. The properties of jacket structure are given in Table 2.

**Table 1**. Properties of DTU 10 MW reference turbine [7].

| Parameter | Value |
|---|---|
| Cut-in, rated, cut-out wind speed | 5 m/s, 11.4 m/s, 25 m/s |
| Rotor, hub diameter | 10 MW |
| Rated power | 178.4 m, 5.6 m |
| Hub height | 119 m |
| Minimum, maximum rotor speed | 6.0 rpm, 9.6 rpm |
| Rotor-Nacelle Assembly (RNA) mass | 676723 kg |
| Moment of Inertia about x-axis of RNA | $1.66\times10^{8}$ kg-m² |
| Moment of Inertia about y-axis RNA | $1.27\times10^{8}$ kg-m² |
| Moment of Inertia about z-axis RNA | $1.27\times10^{8}$ kg-m² |

**Table 2.** Properties of four-legged jacket structure [6].

| Structural Member | Value |
|---|---|
| Base Width | 34 mm |
| Top Width | 14 m |
| Transition Piece height | 9 m |
| Jacket legs diameter (outer) | 1400 mm |
| Jacket legs wall thickness | 65 mm |
| Level 1 X-brace inner radius | 1060 mm |
| Level 1 X-brace wall thickness | 32 mm |
| Level 2 X-brace inner diameter | 940 mm |
| Level 2 X-brace wall thickness | 20 mm |
| Level 3 X-brace inner diameter | 850 mm |
| Level 3 X-brace wall thickness | 24 mm |
| Level 4 X-brace inner diameter | 840 mm |
| Level 4 X-brace wall thickness | 16.5 mm |
| Horizontal braces diameter | 1040 mm |
| Horizontal braces wall thickness | 32-52 mm |
| Pile diameter | 2438 mm |
| Pile wall thickness | 20 mm |

### 2.2 Soil data

A layered sandy soil profile is collected from Von Borstel [6] which is used for the soil domain. The soil data is available up to a depth of 90 m. The effective unit weight, friction angle, and modulus of elasticity of soil are also available. The depth-wise design parameters for the soil are summarized in Table 3.

# 3 Load Calculation

Various loads such as wind, wave, 1P, and 3P loads acting on the OWT structure are discussed in the following section. The wind speed is considered as 11.4 m/sec, the wave period is 8 sec, and the significant wave height is taken as 2 m. The depth of water is considered as 50 m.

**Table 3.** Soil profile used in the numerical model [6].

| Soil type | Depth (m) | Effective unit weight, γ' (kN/m³) | Friction angle, ϕ (deg.) | Modulus of elasticity, E (MPa) |
|---|---|---|---|---|
| SAND | 0 – 2 | 9 | 35 | 7.1 |
| SAND | 2 – 9 | 9 | 35 | 13.1 |
| SAND | 9 – 10 | 9 | 35 | 18.2 |
| SAND | 10 – 15 | 9 | 35 | 20.8 |
| SAND | 15 – 20 | 10 | 35 | 24.9 |
| SAND | 20 – 22.5 | 10.5 | 35 | 27.8 |
| SAND | 22.5 – 29 | 11 | 35 | 30.9 |
| SAND | 29 – 34 | 11 | 35 | 34.7 |
| SAND | 34 – 38 | 11 | 35 | 37.4 |
| SAND | 38 – 40 | 11 | 35 | 39.1 |
| SAND | 40 – 90 | 11 | 35 | 50.3 |

## 3.1 1P loading

A wind turbine is subjected to cyclic loading with the rotational frequency, and the source of this load is primarily due to the rotor mass imbalance and aerodynamic imbalance. The amplitude of this forcing depends on the extent of the imbalances [8,9] is estimated as:

$$F_{1P} = 4\pi^2 I_m f^2 \tag{1}$$

where $I_m = mR$ and $I_m$ is the mass imbalance with units of kgm, $m$ is a lumped mass, and $R$ is the radial distance from the centre of the hub along the blade.

## 3.2 3P Loading

The wind produces drag force on the tower, which can be considered constant at given mean wind speed, ignoring buffeting and vortex shedding on the tower and also without the effect of the rotating. When a blade passes in front of the tower, it disturbs the flow downwind and decreases the load on the tower. The frequency of this load loss is three times the rotational frequency of the turbine 3P [8,9,14],

$$F_{3P}=F_{drag}R_A \tag{2}$$

$R_A$ is the area ratio given by the ratio of the area of the blade to the area of tower top, $F_{drag}$ is the drag force on the tower.

### 3.3 Wave load

The wave load on the OWT structure is calculated based on Morison's equation [8] as follows:

$$F_W = C_M \rho \Pi D^2 / 4 \int_{dw}^{\eta(t)} \ddot{u} dz + C_D \rho D / 2 \int_{dw}^{\eta(t)} \dot{u}|\dot{u}| dz_2 \tag{3}$$

where $C_M$ and $C_D$ are the mass and drag coefficient of the tower. $D$ is the diameter of the jacket leg in m, $\rho$ is the mass density of the seawater (1030 kg/m$^3$), $d_w$ is the depth of water in m $\dot{u}$ , $\ddot{u}$ are the velocity and acceleration of wave-induced water in the horizontal direction, $\eta(t)$ is the surface wave profile based on linear wave theory (Airy theory) and given by [8]:

$$\eta(t) = 0.5 h_w \cos(kx - \omega_w t) \tag{4}$$

The expression of $\dot{u}$ and $\ddot{u}$ according to DNV-RP-C205 [2010] and DNV GL-ST-0126 [2016] as follows:

$$\dot{u} = \frac{h_w \pi}{T_w} \frac{\cosh(k(z_2 + d_w))}{\sinh(kd_w)} \cos(kx - \omega_w t) \tag{5}$$

$$\ddot{u} = \frac{2 h_w \pi^2}{T^2{}_w} \frac{\cosh(k(z_2 + d_w))}{\sinh(kd_w)} \sin(kx - \omega_w t) \tag{6}$$

where $h_w$ is the height of the wave in m and is taken as 2 m in the present study, $k$ is the wavenumber in m$^{-1}$, $\omega_w$ is the frequency of the wave in rad/s, $d_w$ is the depth of water in m, $T_w$ is the period of the wave in s, $z_2$ is the depth below the sea surface in m.

### 3.4 Wind load

Wind load acting on the tower is divided as (a) load acting on the turbine blade at the hub ($F_b$) and (b) load acting on the tower ($F_D$). wind thrust on the hub ($F_b$) is given in [8,9,12].

$$F_b = 0.5 \rho_a \Pi R_T{}^2 U^2 C_T{}^2 (\lambda_S) \tag{7}$$

where $R_T$ is the radius of the rotor in m. $\rho_a$ is the density of the air at 15ºC and 1 atm pressure, which equals 1.225 kg/m$^3$. $C_T(\lambda s)$ is the thrust coefficient which depends on tip speed ratio ($\lambda_s$) and is given by:

$$\lambda_s = V_r R_T / U \tag{8}$$

where $V_r$ is the speed of the rotor in rad/s, $U$ *is* the speed of the wind at the hub level in m/s. The summary of loads acting on the offshore wind turbine is given in Table 4.

**Table 4.** Summary of loads on OWT

| Direction | Loads | Force (MN) | Forcing frequency (Hz) |
|---|---|---|---|
| Fore-aft | Wind load on hub, $F_b$ (dynamic) | 0.842 | 0.01 |
| | Wave load, $F_w$ (dynamic) | 0.184 | 0.1 |
| | 3P load, $F_{3P}$ (dynamic) | 0.006 | 0.48 |
| | Tower drag, $F_D$ (static) | 0.022 | NA |
| | Current | 0.013 | NA |
| Side-to-side | 1P load | 0.0068 | 0.16 |

### 3.5 Seismic load

To study the effect of seismic load on the jacket supported offshore wind turbine, the model is excited at the base of the soil domain in all three directions by the modified EI-Centro earthquake of 1979, which has a peak ground acceleration 0.1g. The duration of the earthquake is 18.38 sec (Fig. 2).

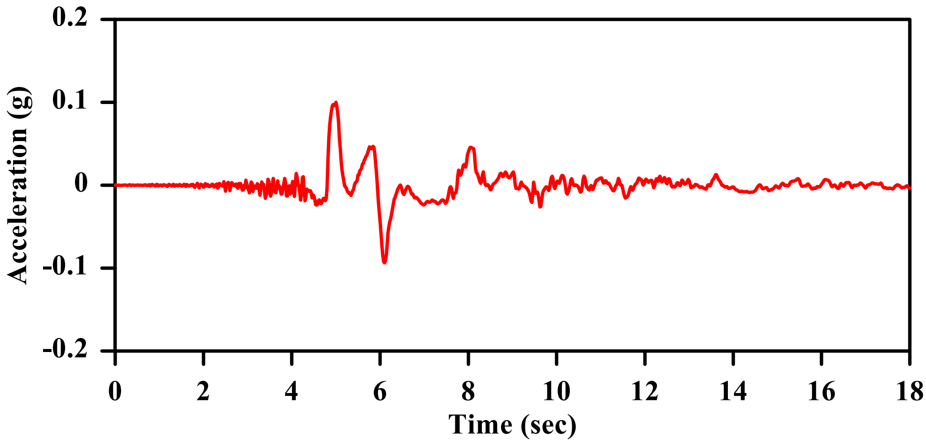


**Fig. 2.** Acceleration time history of El-Centro (1979) earthquake.

## 4 Model Parameters

A parametric study is conducted to examine the effect of aspect ratios of pile length ($L_p/D$) and the jacket ($h/L_B$) on the rotation of monopile and the tower. The diameter of the pile, pile thickness, and total height ($h$) is kept constant. The ratio of base width to top width of jacket is taken as 2.4. A total of nine models were created by selecting various combinations of pile length and jacket base width which is given in Table 5.

**Table 5.** Range of parameters for parametric study

| Parameters | Values (m) |
|---|---|
| Jacket Base width ($L_B$) | 34, 24, 18 |
| Pile Length ($Lp$) | 40, 20, 10 |
| Pile diameter ($D$) | 2.438 |
| Pile thickness ($t_w$) | 0.04 |
| Height of the tower above mudline ($h$) | 157.63 |

## 5 Results and Discussion

The change in responses of Offshore Wind Turbine with respect to the variation of aspect ratios of pile and jacket are discussed in the following section

### 5.1 Validation of numerical model

The model is validated by comparing the obtained natural frequency of (a) tower only and (b) the whole structure with that of given in INNWIND.EU report [6]. The natural frequencies are found to be matching reasonably well with that of reported values in the literature [6]. The maximum variation between the obtained and reported natural frequency lies within 3%. The detailed descriptions of observed and reported natural frequencies are given in Table 6.

**Table 6.** 3D FE analysis and the reported natural frequencies of tower and whole structure.

| Structure | Mode | 3D Finite Element | Reported values in [9] |
|---|---|---|---|
| Tower only | 1st bending side-side | 0.329 | 0.324 |
| | 1st bending fore-aft | 0.332 | 0.327 |
| Total structure | 1st bending side-side | 0.278 | 0.286 |
| | 1st bending fore-aft | 0.281 | 0.288 |

### 5.2 Effect of pile length on natural frequency

Offshore wind turbines are dynamically sensitive structures, and estimating natural frequency considering soil-structure interaction is one of the primary design criteria. OWT is designed such that the natural frequency of the whole system (jacket, tower, and pile) needs to be sufficiently away from 1P (rotor frequency), 3P (blade passing frequency), and wave excitation frequency. In this study, a 10 MW wind turbine is selected, and geometric descriptions are given in Table 2. The 1P frequency range of 10 MW wind turbine is 0.1 - 0.16 Hz, and the wave excitation frequency is 0.1 Hz, and therefore the required frequency range is between 0.2 - 0.28 Hz [13]. All geometric dimensions and diameter of the pile are kept constant, and the variation of the overall natural frequency of the structure is studied by varying the length of the pile (i.e., the vertical stiffness of foundation). The fixed base natural frequency of OWT is 0.286 Hz. The variation of natural frequency with pile length is shown in Table 7. As the vertical stiffness of the foundation increases, the vibration mode moves to sway-bending, and the corresponding first natural frequency increases and approaches the fixed base natural frequency [3]. Similarly, at a pile length of 40 m, the natural frequency was found to be almost matching with the fixed base natural frequency, and this difference (11%) is maximum when pile length is 10m. This variation shows the influence of the length of the pile in natural frequency.

**Table 7.** The variation of natural frequency with pile length.

| Pile penetration (m) | Natural frequency (Hz) |
|---|---|
| 40 | 0.278 |
| 25 | 0.261 |
| 20 | 0.257 |
| 10 | 0.248 |

### 5.3 Effect of geometry of jacket and pile on OWT responses

The natural frequency of the overall structure ($f_o$) corresponding to various aspect ratios of jacket and embedded length of the pile and are obtained and are normalized with the natural frequency of tower ($f_{fb}$) clamped at the bottom and is shown in Fig (3) The ($f_0/f_{fb}$) decreases with an increase in ($h/L_B$) ratios. The natural frequency is found to be increasing with an increase in the bottom width of jacket ($L_B$) and embedment length of the pile ($L_p$). As the pile length increases, the vertical stiffness of the foundation increases, and the mode of vibration tends to sway bending mode, and the natural frequency comes close to the fixed base natural frequency (cf. Fig. 3).

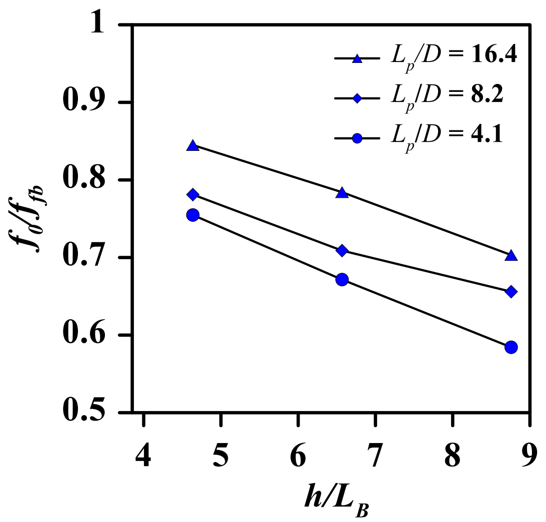


**Fig. 3.** Variation of the natural frequency with respect to aspect ratios of pile and jacket.

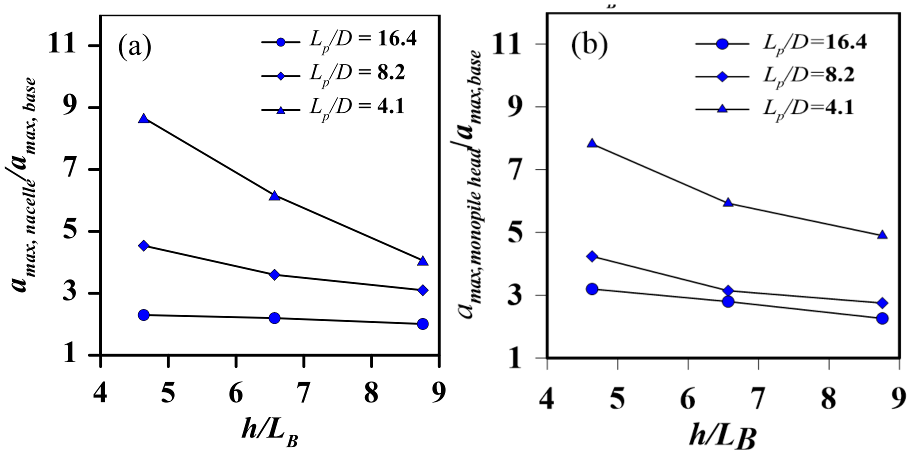


**Fig. 4.** Amplification of maximum vertical acceleration: (a) at the tower to and (b) monopile head.

The amplification of vertical acceleration at tower top and monopile head with respect of base input motion is examined and presented in Fig. 4(a)-(b) for various $h/L_B$ and $L_p/D$ values. It can be observed that as the embedment length of the pile decreases, the amplification of acceleration increases than that of base input motion. The maximum amplification in acceleration occurs in the case of minimum pile length. Also, at higher $L_p/D$ ratios, amplification of acceleration does not seem to have much influence on the base width of the jacket. However, at the low $L_p/D$, the amplification is found to be increasing with an increase in the base width of the jacket. A similar observation is observed in amplification at the tower base (cf. Fig. 4b).

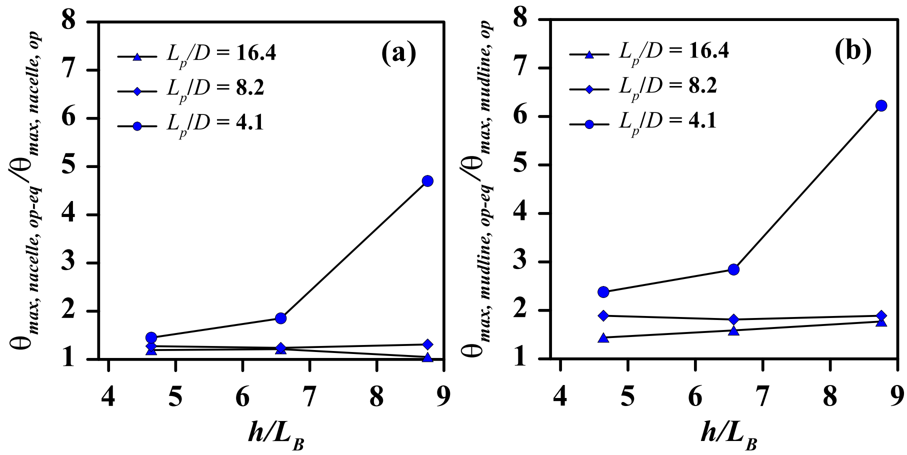


**Fig. 5.** Variation of ratio of rotation due to operational and seismic load and operational load at (a) tower top and (b) monopile at mudline in the side- side direction.

Fig. 5(a) shows the variation of the ratio of maximum rotation in side-side direction due to operational and seismic load to the maximum rotation due to operational load only at tower top for various $h/L_B$ and $L_p/D$. It is observed that the base width of the jacket has a marginal influence on the increase in the rotation due to the application of seismic load for long piles (i.e., $L_p/D$= 8.2 and 16.4). However, for a lower $L_p/D$ ratio, the increase in the rotation due to seismic load increases about 3 times as the base width decreases. A similar observation can be seen for the maximum mudline rotation of monopile (Fig. 5(b)).

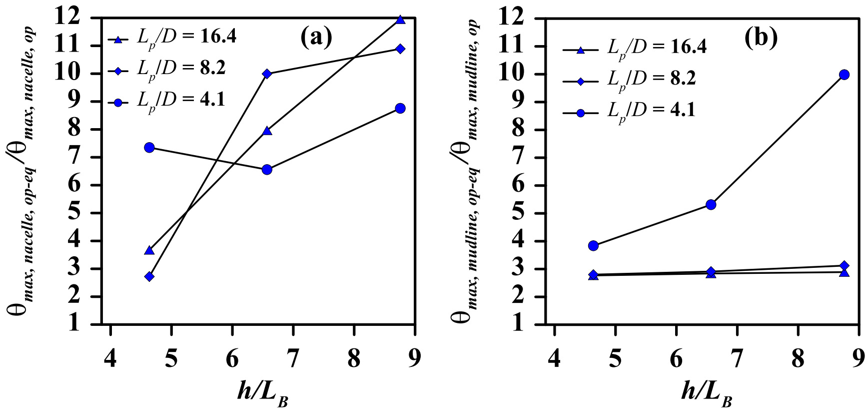


**Fig. 6.** Variation of ratio of rotation due to operational and seismic load and operational load at (a) tower top and (b) monopile at mudline in the fore-aft direction.

Fig. 6 shows the variation of ratio of maximum rotation due to operational and seismic load to the rotation due to operational load at the fore-aft direction. It is observed that as the length of the pile decreases, there is an abrupt increase in rotation (4 times) that takes place due to seismic load on an offshore wind turbine. This is attributed due to the rocking mode of vibration at a shorter pile length.

## 6 Conclusions

This study presents the effect of the base width of the jacket and embedded length of the pile on the vertical amplification of acceleration and the maximum response of monopile and tower. The variation of natural frequency with respect to pile length is also examined. The dynamic analysis is carried out using a three-dimensional finite element model. It is found that the natural frequency was found to be almost matching with the fixed base natural frequency at a pile length of 40 m, and the difference is found to be maximum at a pile length of 10 m. It was also found that the natural frequency of OWT decreases with a decrease in foundation spacing. A four-fold increase in the maximum rotation of monopile at mudline and tower top is observed in side-side direction due to the application of seismic load for a shorter pile. The amplification of response is found to be about 10-12 times in the fore-aft direction due to the application of seismic load for shorter pile length. For a higher $L_p/D$ ratio, the variation of the bottom width of the jacket does not show much influence on the rotational response. However, it is found to be significant for a lower $L_p/D$ ratio. The finding from this study could be a useful input for the optimal design of the jacket supported OWT structure in seismically active areas.

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