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Dynamic Response of Offshore Articulated Tower-Under Correlated Wind and Wave

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Abstract - Articulated tower is a compliant offshore structure that oscillates freely with environmental loads of wind and wave. Present study deals with the dynamic response of a single hinge Articulated tower. Hydrodynamic loading of the tower is computed using Morrisons equation. Acceleration and velocity terms used in Morrison equation is computed first by Airy theory and then by Stokes theory. Various responses of the Articulated tower are studied and a comparative analysis is done so as to see which of Airy wave and Stokes wave gives better response. Response of this Articulated tower is then studied under wave alone environment and wind+wave correlated environment. Fluctuating component of the wind is modelled by Simiu's spectrum, while the sea state is characterized by Pierson-Mosokowitz (P-M) spectrum. Random waves and wind are simulated by Monte Carlo simulation technique. Response of Articulated tower is determined by time domain iterative method using Newmarks's -β integration scheme. It is concluded that Stokes wave gives improved response and presence odd wind forces along with the waves amplify the responses significantly particularly at lower frequencies.

Key Words: P-M (Pierson-Mosokowitz), A-F(Axial Force), A-T(Articulated Tower), (M-E) Morrison Equation, (A-T) Airy Theory, (S-T) Stokes Theory.

1.INTRODUCTION

Articulated Tower is a flexible complaint offshore structure which resist the environmental forces through the action of compliancy, which means that one single buoyant shell with sufficient buoyancy is used to restore moment against the lateral loads.Articulated towers are designed such that their fundamental frequency is well below the wave frequency to avoid dynamic amplification. Dynamic interaction of these towers with environmental loads (wind, waves and currents) acts to impart a lesser overall shear and overturning moment due to compliance to such forces. This compliancy introduces geometric nonlinearity due to large displacements, which becomes an important consideration in the analysis of articulated towers.Wind and wave loadings have a predominant role in the design of an offshore structure for a successful service and survival in harsh sea conditions. The flexibility of the new generation,Wind and wave loadings have a predominant role in the design of an offshore structure for a successful service and survival in harsh sea conditions. compliant structures (articulated tower, guyed tower and tension leg platforms) give rise to naturalperiods ranging from 1 to 100 seconds. Such structures comply in the direction of environmental loads and results in an increase in their sensitivity to the dynamic effects of wind. Fixed structures will respond them in virtually static fashion. For fixed platforms,contribution of lateral wind loads for the design is only 10% of the global loads. While in case of compliant platforms, it increases to 25%.

Tower Response Under Correlated Wind and Wave.

After analysing the results obtained by Airy theory and Stokes theory, Stokes theory is selected to perform the further analysis of Articulated tower under correlated wind and wave as it gives improved responses. For wind analysis the schematic diagram of the superstructure of Articulated tower is shown in figure 1.

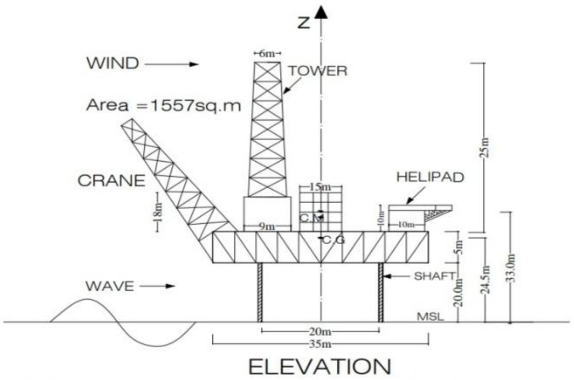

Figure 1.Superstructure detail for wind load assessment

Multiple point simulation technique is used to perform wind load assessment as it includes partial correlation over the entire superstructure resulting in lower response estimates than the single point simulation. Platform shaft is divided into 50 elements to represent hydrodynamic loading adequately. The deck mass above the top shaft is lumped at the C.G of the platform. A constant current velocity of 1m/s is assumed for the analytical study. The overall drag coefficient for the tower portion on which wind acts is 0.002. Moderate sea state and high sea state are considered in the study and values are given in Table 1.Other characteristics of the wind is given in Table 2 .In moderate sea state wind velocity is taken as 15m/s while in high sea state wind velocity is taken as 25m/s. For plotting PSDF's the wind fluctuations are represented by Emil Simiu's spectrum. Comparative Time Histories and PSDF's are then plotted between wave alone environment and wind+ wave correlated environment.

Sea state description	Significant wave height, H_s(m)	Zero crossing period, T_Z (s)	Wind velocity (m/s)
Moderate sea state	4.51	7.38	15
High sea state	12.4	12.23	25

Table 1.Characteristics of different sea states

Characteristics	Values
Water depth	350m
Mass density of sea water	1025 Kg/m^3
Air density	1.27 Kg/m^3
Current Velocity	1.0 m/s
Drag coefficient (C_d)	0.6
Inertia coefficient (C_m)	2.0
Wind drag co-efficient (C_d)	0.002
Aerodynamic center above SWL	33
Total equivalent area for wind load	1557 m^2
Emil Simiu's wind spectrum constants	
β	6.0
fs	0.2
fm	0.07
Roughness length (z_0)	0.001266 m
Length of longitudinal turbulence (L_u)	180 m

Table 2.Characteristics of the wind

Advantage of Articulated Tower

- Very large fundamental sway period so dynamic amplification factor is much less than fixed structure.
- Enhanced "turnability "of periods of the system for a particular site. An adjustment of natural frequency could be assisted by set up of a ballast water chamber positioned above the connector joint.
- Articulate loading platforms are re-usable. Once an oil reservoir is depleted, it can be easily relocated to other field at a minimal cost.
- Articulated loading platforms are used as a portable offshore system for the moored tankers. Such configuration is particularly suitable for fields that have a limited production capability, or are too far off from refining to justify the laying of pipe line.

Articulated Towers around the Word Ocean

Field	Type	Installation Year	Water Depth	Operator	Platform Function
Beryl	Articulated loading Tower	1975	117	Ben C. Gerwick	Loading Tower
Stafford	Articulated Tower	1978	145	EHM	Loading and Mooring
Maureen	Gravity articulated tower	1982	490	Howard Doris Ltd.	Drilling and production
North East Frigg .	Single Hinge Articulated Tower	1983	150	Total E&P UK Ltd	Field control station & gas Prod
Garden Banks	Compliant articulated tower (CAT)	1998	501	Amerada Hess Corp.	Drilling and production

Need of Articulated Tower in Indian Scenarios

In India Oil has been found at the shallower depth usually up to 100-150 m.Articulated tower can be advantageously used for such a shallow depth. As depth of exploration increases the possibility of finding oil and gas in deeperwater increase. As depth of water increases, size of conventional fixed legplatform will cross their effective economic size making it unsuitable. So there arises a need of new structural systems to be effectively used in deeper water. One such solution is articulated Tower which take advantage of the effect of compliance, i.e., yield to the environmental forces. With the discovery of Oil and Natural gas in the deeper water, there arises a need of economical solution of offshore structure. Conventional fixed leg platform is found to be economical for shallow depth. As depth of water

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increases, size of these platform will cross their effective economic size making it unsuitable. So there arises a need of new structural systems to be effectively used in deeper water. One such solution is articulated Tower which take advantage of the effect of compliance, i.e., yield to the environmental forces.

Reliability of Articulation System

Various environmental loads such as Wind load, wave load, ocean currents etc are continuously applied on the articulate towers. These oscillating stresses can cause various type of damage to the structure such as metal fatigue which is caused due to stress concentration of various shear and axial forces.

Various researchers have done remarkable work in combat the problem of designing articulate joint.

Author	**Year**	**Salient Features**
Chen and Will	1999	• Fatigue and wear studies were carried out on new generation, Baldpate compliant tower. • They concluded that the impact on the fatigue damage due to low frequency responses, particularly wind loads are significant and can not be ignored. • They also presented an approach for predicting wear volumes at axial tube guides and conductor guides of the tower
Islam and Zaheer	2008	• Effect of low frequency wind forces with random waves which excited on double hinge articulated tower is seen to do the dynamic response analysis. • Emil Simiu's spectrum is used to model fluctuating component of wind velocity. • Pierson-Moskowitz spectrum is used to characterized the sea state. • Newmark's β integration scheme has been employed which solves the equation of motion in an iterative fashion.

Objective

- To select a theory which gives improved responses, and by using that, to do investigation of the responses of a model Articulated Tower to random wave force alone and to the combined effect of wind, wave and current forces.

2. Methodology

In the present work firstly a nonlinear dynamic analysis of the said structure under waves / earthquake has been carried out for its time domain responses using Langrangian approach which has the capability of equating kinetic and potential energies of the system to the rotational degrees of freedom. The random waves have been simulated by Monte-Carlo technique represented by Modified PM spectra. Modified Morison's equation has been used for estimation of hydro-dynamic loading. Water particle kinematics has been governed by Airy's linear wave theory and Stoke's fifth order theory. Result obtained from both the theory are compared with each other. To incorporate variable submergence, Chakraborty's correction [20 & 21] has been applied. Seismic inputs have been applied using Northridge, Imperial valley CA, Duzce, Turkey spectra. Stability assessment has been carried out using concept of minimum potential energy and two-dimensional phase plots. Analysis of the response of Articulated Tower to fluctuating Wind and Wave Forces is done by a time domain iterative procedure which includes the structural as well as forcing nonlinearities.

Modelling of the Articulated Tower

Modelling of Articulated Tower will be nonlinear. Three type of nonlinear matrix will be formed. Stiffness matrix which consist of fluctuating Buoyancy component, Mass matrix which consist of two type of mass, one is structural mass and other being the added mass due to the motion of Tower and third matrix will be the Damping matrix. The tower structure is idealized by replacing its mass distribution with discrete masses located at the centroid of a series of small cylindrical elements of equivalent diameter Di representing inertia, added mass and buoyancy. All forces are assumed to act at these centroids. In submerged part the forces act is weight, inertia, buoyancy and fluid force while wind force acts on exposed area.

Fluid Forcing

The environmental forces of wind, waves and currents are categorized as non-conservative forces .The forcing function Q_θ is the moment of the dynamic forces acting on the platform at any instant of time given by

$$Q_\theta = F_a(u(z),\dot{u},\dot{x}) + F_d(\dot{u},v_c,\dot{x}) + F_i(\ddot{x}) \quad (01)$$

in which $F_a(u(z),\dot{u},\dot{x})$ is aerodynamic force, $F_d(\dot{u},v_c,\dot{x})$ is fluid drag force and $F_i(\ddot{x})$ is fluid inertia force. These loads are defined in the following subsections.

Wind Load

The portion of the articulated tower above the water surface is subjected to aerodynamic force predominantly resulting from wind drag force. This force consists of mean and fluctuating components. The later component produces the dynamic wind force. For formulating fluctuating components of wind on the tower superstructure, wind fluctuations are described as a single-point or multiple-point wind field. The wind force per unit of projected area is given by:

$$f(y,z,t) = 0.5\rho_a C_p(y,z)[u(z)+u'(y,z,t)-\dot{x}(t)]^2 \quad (02)$$

where $C_p(y,z)$ is the wind pressure coefficient, $\dot{x}$ is the structural velocity in the horizontal direction

ρ_a is the air density; u(z) is the mean wind velocity, and u'(y,z,t) is the fluctuating wind velocity

$$F_a(y,z,t) = \int f(y,z,t)dydz \quad (03)$$

, this integral is to be done over the total projected area.

Mean wind estimation

The mean description of the turbulent wind is assumed to be governed by the logarithmic law as

$$u(z)=u(z_{ref})= ln\frac{z}{z0}/\ ln\frac{zref}{z0} \quad (04)$$

where z_{ref} is the reference elevation usually taken as 10m above mean sea level, z the vertical coordinate above MSL at 33.0 m . The gustiness of the wind is due to the level of turbulence in the wind. Turbulence intensity (*I*) is defined in International Electrotechnical Commission (IEC) and Germanischer Lloyd (GL) standards as a function of wind speed. Offshore turbulence is less than on-land turbulence, and turbulence intensity is low for high wind speeds. For wind velocity of 25 m/sec, turbulence intensity is taken as 0.12, whereas, for a wind velocity of 15 m/sec, turbulence intensity is taken as 0.15 (Karimirad *et al.* 2011).

z_0 the roughness length which is provided by specifying the value of sea drag coefficient, defined as

$$C_{d(sea)} = \left(\frac{k}{ln(\frac{10}{z0})}\right)^2 \quad (05)$$

where K is the Von Karman constant (K = 0.4). The following empirical relations were proposed C_{Dsea} based on many measurements for the range $4<u(10)<21$ m/sec, Simiu and Leigh (1984).

$$C_{Dsea} = 5.1 \times 10^{-4}[u(10)]^{0.46} \quad (06)$$

$$C_{Dsea} = 10^{-4}[7.5 + 0.67u(10)] \quad (07)$$

For $u(10)>20$ m/sec, C_{Dsea} may be obtained by taking the average of the values given in equation. (06) and (07). In another study, Donelan *et al.* (2004) used variable roughness length based on wind velocity. Roughness length $z_0$is higher for high wind velocity. Here, we used a constant roughness length, z_0= 0.001266 m (for wind velocity of 25 m/sec) to simplify the analysis.

Fluctuating wind simulation

In order to predict the response of an articulated tower to fluctuating wind forces, it is necessary to define the spectrum of wind fluctuations. Simiu and Leigh (1984) developed the spectrum for compliant platforms, expressions for which are given below:

$$\frac{n\ S_u(z,n)}{U_*^2} =\{a_1f+b_1f^2+d_{1f}^3\}\ 0<f<f_m \quad (08)$$

$$\frac{nS_u(z,n)}{U_*^2} =\{\ c_{2f}+b_2f^2+a_2f^3\}\ f_m<f<f_s \quad (09)$$

$$\frac{nS_u(z,n)}{U_*^2} =\{0.26f^{-2/3}\}f>f_s \quad (10)$$

where f_m is the frequency in the micro scale region of wind spectrum (= 0.07), f_s is the frequency in the inertial subrange (= 0.2), and S_u is the spectrum of longitudinal velocity fluctuations

$f\ = non\ dimensional\ frequency, f = \frac{n(z)}{u(z)}$

U_* is the friction velocity, $U_* = \frac{ku(10)}{ln(\frac{10}{z_0})}$

Detailed expressions of $a_1;b_1;d_2;c_2;a_2;b_2$ are given in Simiu and Leigh (1984).

Wind Field Simulation

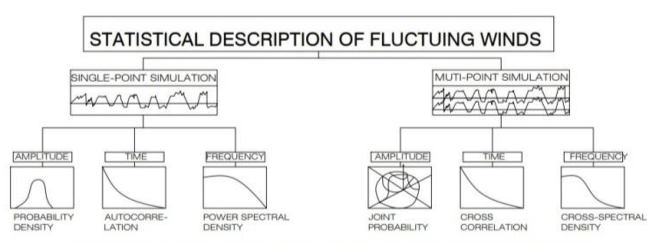

Figure 2. Statistical Description Of fluctuating Winds

Deck Displacement

Deck displacement under moderate sea state

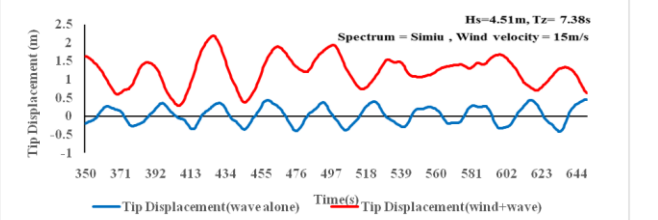

Figure 3.Time History of Deck Displacement by wave alone and wind+wave under moderate sea state.

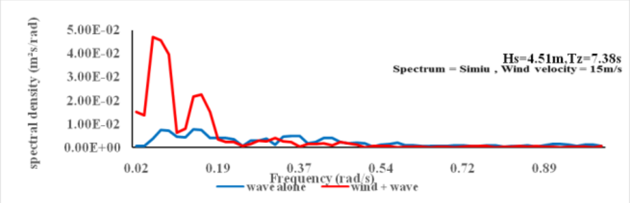

Figure 4.PSDF of Deck Displacement by wave alone and wind+wave under moderate sea state.

Deck displacement under high sea state

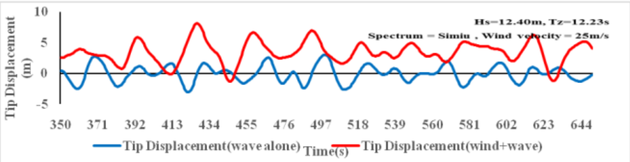

Figure 5.Time History of Deck Displacement by wave alone and wind+wave under high sea state.

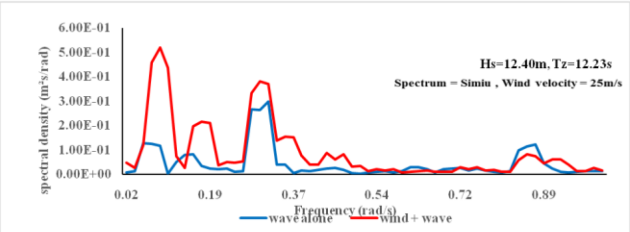

Figure 6. PSDF of Deck Displacement by wave alone and wind+wave under high sea state.

Sea State	Statistics	wave alone	wind+ wave
Moderate	Maximum	0.47	2.18
	Minimum	-0.50	0.29
	Mean	0.02	1.25
	Standard Deviation	0.25	0.38
High	Maximum	3.03	8.13
	Minimum	-3.01	-1.33
	Mean	0.01	3.44
	Standard Deviation	1.26	1.71

Table 3.Statistical comparison of Deck Displacement values by wave alone and wind+wave

Hinge Rotation

Hinge rotation under moderate sea states

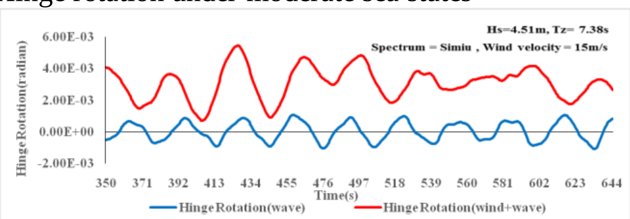

Figure 7.Time History of Hinge Rotation by wave alone and wind+wave under moderate sea state.

Hinge rotation under high sea state

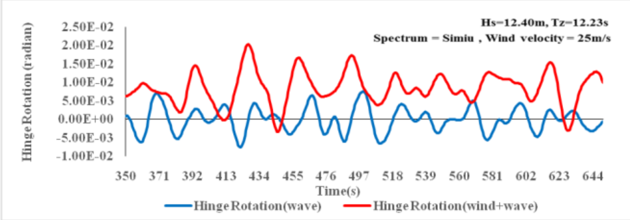

Figure 8.Time History of Hinge Rotation by wave alone and wind+wave under moderate sea state.

Hinge Shear

Hinge shear under moderate sea state

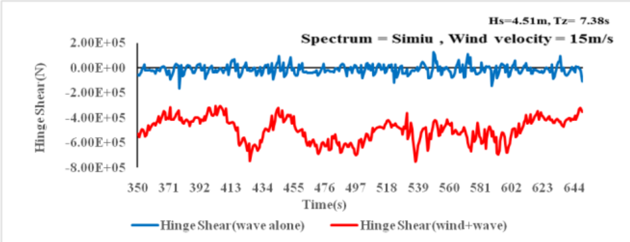

Figure 9.Time History of Hinge Shear by wave alone and wind+wave under moderate sea state.

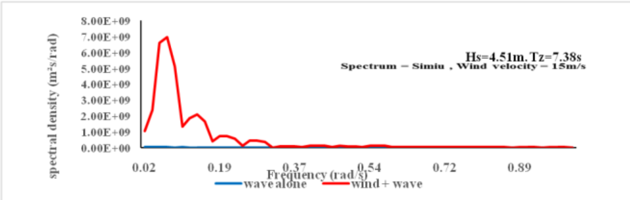

Figure 10. PSDF of Hinge Shear by wave alone and wind+wave under moderate sea state.

Hinge shear under high sea state

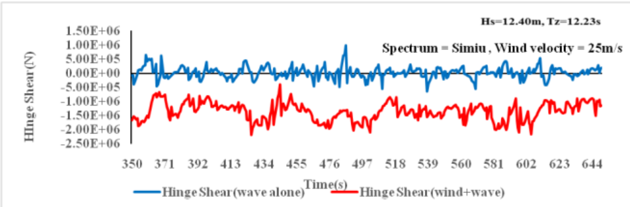

Figure 11.Time History of Hinge Shear by wave alone and wind+wave under high sea state.

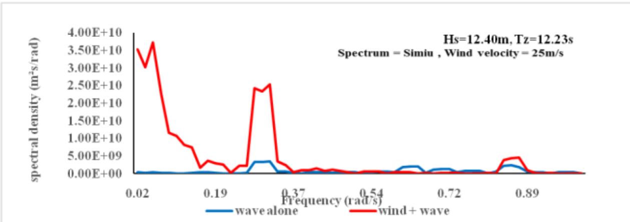

Figure 12. PSDF of Hinge Shear by wave alone and wind+wave under high sea state

Sea State	Statistics	wave alone	wind+wave
	Maximum	1.25E+05	-3.07E+05
	Minimum	-1.65E+05	-7.50E+05
	Mean	-1.47E+04	-4.95E+05
	Standard Deviation	3.66E+04	9.54E+04
	Maximum	9.76E+05	-3.92E+05
	Minimum	-6.41E+05	-2.18E+06
	Mean	1.93E+04	-1.35E+06
	Standard Deviation	2.02E+05	3.13E+05

Table 4.Statistical comparison of Hinge Shear values by wave alone and wind+wave.

Axial Force

Axial force under moderate sea state

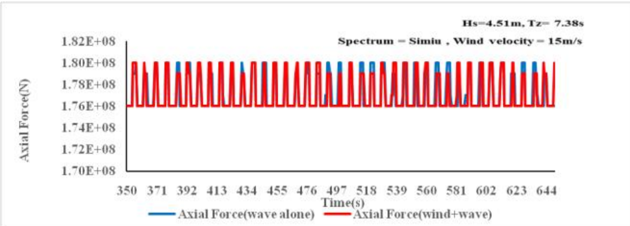

Figure 13.Time History of Axial Force by wave alone and wind+wave under moderate sea state.

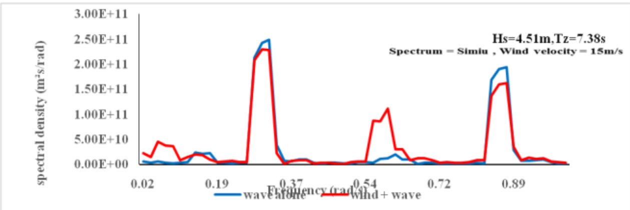

Figure 14.PSDF of Axial force by wave alone and wind+wave under moderate sea state.

Axial force under high sea state

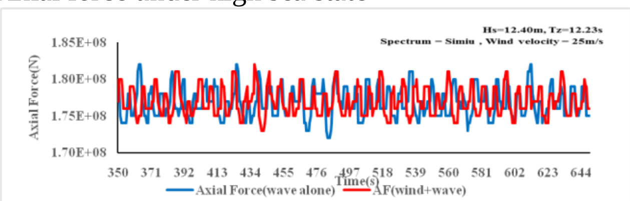

Figure 15.Time History of Axial Force by wave alone and wind+wave under high sea state.

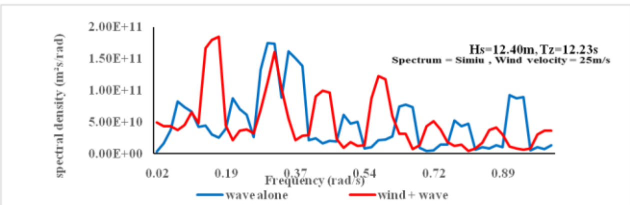

Figure 16.PSDF of Axial Force by wave alone and wind+wave under high sea state.

3. CONCLUSIONS

In the present study Articulated offshore tower has been investigated. First the hydrodynamic loads on the Articulated tower is estimated by using the Airy theory, which is a linear wave theory and is frequently used where surface is not changing or change is too small to notice. Then the hydrodynamic loads are estimated by more rational Stokes 5th order theory which takes into account the surface variation of waves. Results of time histories, PSDF's and statistical values shows that the responses obtained by using Stokes theory are improved responses and are in line to the actual responses to a large extent.

For further analysis of Articulated tower, Stokes wave is selected for computing Hydrodynamic loads. Comparative study of responses computed by the wave load alone and wave+wind combined has been done.

The comparative results of Time Histories, PSDF's and statistical values shows that the combined effect of wind and wave is more severe than wave alone effect mainly at the low frequency excitation of the Articulated tower since the fluctuating component of wind velocity has very low frequency energy content, so the wind induced vibration of the platform comes out to be significant.

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