JSEE Spring 2009, Vol. 11, No. 1

Technical Note

Earthquake Response of a Multi-Articulated Offshore Tower in Random Sea

S. Danish Hasan[1], **N. Islam**[2], **and K. Moin**[3]

1. Associate Professor, Civil Engineering Section, University Polytechnic, AMU, Aligarh, India, email: sd_hasan@rediffmail.com
2. Professor, Dept. of Civil Engineering, Jamia Millia Islamia, New Delhi, 25, India
3. Professor and Head, Dept. of Civil Engineering, Jamia Millia Islamia, New Delhi, 25, India

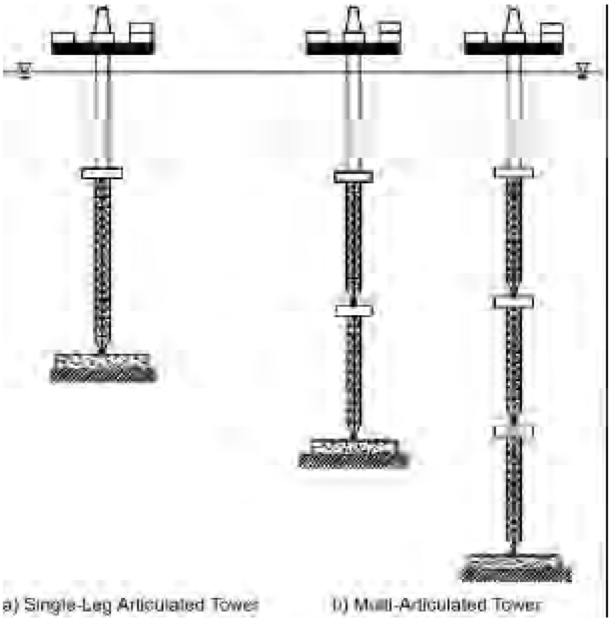
ABSTRACT

The present study deals with the seismic compliance of a multi-articulated offshore tower to three real (El Centro 1940, Taft 1952 and Northridge 1994) earthquakes in a random sea environment. The random waves are generated using Monte-Carlo simulation with the Pierson-Moskowitz (P-M) spectrum. The shafts of the tower are idealized as a rigid cylindrical column with 2 rotational degrees of freedom. Seismic forces are evaluated by dividing the tower into finite elements with masses lumped at the nodes. The earthquake response is carried out by random vibration analysis, in which, seismic excitations are assumed as a broadband stationary process. The dynamic equation of motion is solved in time domain. Nonlinearities due to variable submergence and buoyancy, added mass along with the geometrical nonlinearities associated with the system are taken into account. The results are expressed in the form of time-histories of the response quantities. Power spectral densities under different seismic and random sea environments are plotted.

Keywords:
Multi-articulated tower;
Earthquake time-history;
Spectral density;
Added mass

1. Introduction

Articulated towers are among the innovative compliant offshore structures that are economically attractive in deeper waters. They are light weight and extremely flexible against rotation about the articulating point (s). As a result, large displacements with geometric nonlinearities are the primary dynamic characteristics of these structures. The structure's fundamental frequency is designed well below the wave frequencies. Under deep water conditions, single-leg articulated offshore tower, see Figure (1a), attracts significant bending stresses near its mid height. Therefore, additional articulations are provided, leading to a configuration known as multi-articulated offshore towers, see Figure (1b). Extremely few literatures are available that discusses the structural behavior of such towers under seismic excitation. Instead, much of the work is devoted to wave, current and wind responses [1-4] only. Seismic response is hardly explored. Therefore, response of articulated offshore towers in seismic sea environment (earthquake + wave loads) is of immense importance, especially of multi-articulated offshore towers. Even the latest installation among the articulated towers (Angola, West Africa) has not considered the seismic criteria [5]. In a case study, the seismic response of articulated tower was investigated by modeling it as a stick [6]. The tower was primarily used for mooring. The main emphasis of the study was on the methodology for modal responses rather than the relative significance of seismic and hydrodynamic loadings. Soil-structure interaction was considered but fluid-structure interaction was ignored. Forces on hinge due to seismic forces alone were presented. In another study, the combined effect of seismic and hydrodynamic loadings on a guyed tower was investigated by Ryu and Yun [7]. In their study the effect of hydrodynamic damping was incorporated while the hydrodynamic drag force was linearized.



a) Single-Leg Articulated Tower　b) Multi-Articulated Tower

Figure 1. Different types of articulated offshore towers.

The other sources of nonlinearities have neither been incorporated nor been discussed. Lina et al [8] in their study examined the effect of different water depths on the response of articulated tower subjected to seismic excitation in still waters, while, the nonlinear dynamic behavior of the tower under various sea states along with an earthquake force was investigated by Islam and Ahmad [9-10]. Wu and Chen [11] too studied the effect of support excitation with elastic and fixed support conditions for an offshore tower. The tower carried an eccentric tip mass with rotary inertia. Similarly, Chandrasekaran and Gaurav [12] in their study had emphasized that even the stiff degree-of-freedom like heave should be closely monitored for its threshold values, particularly considering vertical seismic excitation for triangular compliant *TLP*. Therefore, in the light of the available literatures, it is revealed that there is a need to investigate the response of multi-articulated offshore towers under different seismic sea environments. Herein, the objective of the study is to investigate the effect of earthquakes and ocean waves acting simultaneously on the structural response (by comparing the response of offshore tower with and without earthquake load), and to establish relative significance of seismic and hydrodynamic response of the tower.

2. Assumptions and Structural Idealization

Assumptions made in the present study are as follows:

1) The shafts of the tower are idealized as a 2-*D* rigid cylindrical column with 2 rotational degrees of freedom, confined in *XZ*-plane, i.e. the plane of environmental loading.
2) The upper shaft of the tower is equipped with up-righting buoyancy chamber along its length, just below the still water level (*SWL*). The lower shaft is attached with a ballast chamber near the sea bed. This arrangement helps in low dynamic positioning of the compliant towers.
3) The base of the tower is fixed against translation and has zero rotational stiffness.
4) For hydrodynamic force calculation, the latticed shaft is replaced by cylindrical pipe of equivalent diameters, see Table (1).
5) For the estimation of seismic forces, the tower is discretized and masses are lumped at the nodes.
6) Sea waves are generated using simulation procedure with modified Peirson-Moskowitz (*P-M*) spectrum in conjunction with Airy's linear wave theory for water particle kinematics.

3. Mathematical Development

A typical multi-articulated offshore tower model considered for the analysis is shown in Figure (2). The equation of motion in terms of rotational degree of freedom under the combined action of waves and earthquake forces is given as:

$$[I^*]\{\ddot{?}\}+[C]\{\dot{?}\}+[K]\{?\}=\left\{M_?^h(t)\right\}+\left\{M_?^{eq}(t)\right\} \qquad (1)$$

where $\{M_?^h(t)\}=$ Dynamic moment due to hydrodynamic loading and $\{M_?^{eq}(t)\}=$ dynamic moment due to earthquake load. $[I^*]$ is the dynamic mass matrix consisting of mass moment of inertias of all the elements (including added mass) about their articulating joint. Added mass is time dependent, as variable submergence is taken into account [13]. $[C]$ is the hydrodynamic damping matrix, $[K]$ is the system stiffness matrix taking into account large deformations and other nonlinearities corresponding to the degrees of freedom. $\{\ddot{\theta}\}$, $\{\dot{\theta}\}$ and $\{\theta\}$ are the vectors of structural acceleration, velocity and displacement, respectively.

The environmental forces, caused by the simultaneous action of earthquake excitation along with the random characteristics of waves $F_i^{h+eq}(t)$, at any instant of time at an element are determined by using Morison's equation as stated:

$$\begin{aligned} F_i^{h+eq}(t) &= \frac{1}{2}\rho_w C_d\,[D_i]\{\dot{u}_i-(\dot{x}_i+\dot{x}_g)\}\left|\dot{u}_i-(\dot{x}_i+\dot{x}_g)\right|+ \\ &\quad C_m\times[m_i]\{\ddot{u}_i-(\ddot{x}_i+\ddot{x}_g)\}-(C_m-1)[m_i]\{\ddot{x}_i+\ddot{x}_g\} \end{aligned} \qquad (2)$$

Table 1. Properties of the multi-articulated offshore tower.

Details of Multi-Articulated Tower	
- Height of lower and upper shafts, L_1 and L_2	300m and 200m
- Top mass, m_d	2.5x10^6N
- Structural mass of lower and upper shaft, m_1 and m_2	44840 and 20000Kg/m
- Height and Mass of ballast chamber, h_{b1} and m_b	149.5m and 20000Kg/m
- Height (h_{by}) and Position (h_{BC2}) of buoyancy chamber from upper articulation	45m and 122.5m
- Position of upper articulation from sea bed	300m
- **Equivalent Diameter for Tower's Chamber**	
▪ Effective diameter for buoyancy, D_{EB}	20.0m
▪ Effective diameter for added mass, D_{EA}	7.50m
▪ Effective diameter for drag, D_{ED}	20.0m
▪ Effective diameter for inertia, D_{EI}	7.50m
- **Equivalent Diameter for Tower's Shaft**	
▪ Effective diameter for buoyancy, D_{EB}	7.50m
▪ Effective diameter for added mass, D_{EA}	4.50m
▪ Effective diameter for drag, D_{ED}	17.0m
▪ Effective diameter for inertia, D_{EI}	4.50m
- **Time Period**	32.24sec, 24.00sec

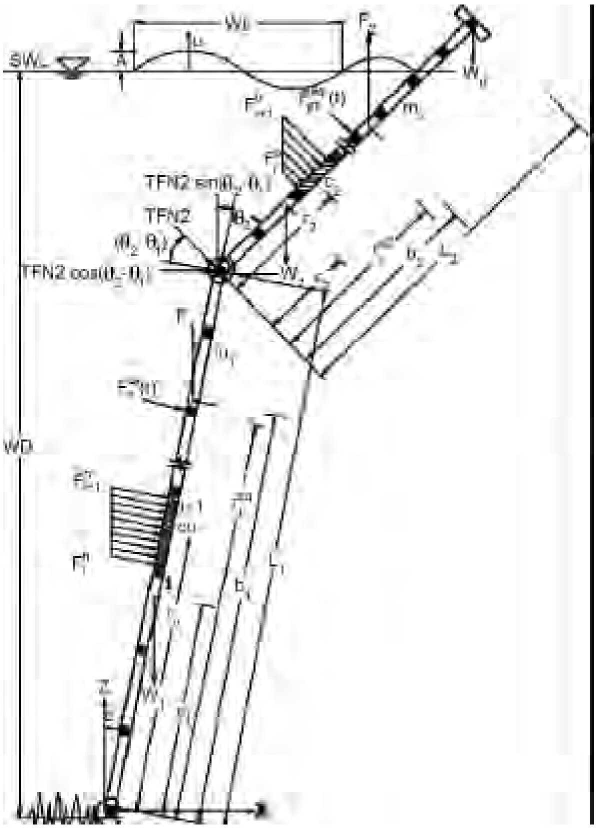


Figure 2. Model of a multi-articulated offshore tower.

The terms C_d and C_m are the drag (C_d= 0.6) and inertia (C_m = 2.0) coefficients respectively. m_i is the elemental mass. $\dot{u}_i, \ddot{u}_i$ are the water particle velocity and acceleration normal to the tower, calculated with the Airy linear wave theory. $\dot{x}_i$ is the velocity of the tower at any instant of time with $\ddot{x}_i$ as its acceleration, while $\dot{x}_g$ and $\ddot{x}_g$ are the seismic ground velocity and acceleration respectively.

4. Numerical Studies and Discussion

A multi-articulated offshore tower, 500m in height with 450m deep water was chosen for the study. The structural details are tabulated in Table (1). The undamped natural frequencies and the vibrational mode shapes were computed by eigenvalue analysis. The natural frequencies of the lower and upper shafts for the fundamental vibration mode are 32.24 and 24.00 seconds respectively.

The seismic response of the tower was carried out by time histories of real earthquakes (Taft 1952; $PGA = 0.18g$, El Centro 1940; $PGA = 0.34g$ and Northridge 1994; $PGA = 0.33g$) in the presence of random sea ($Hs = 6m$, $Tz = 12sec$). The components $S69E$, $N00S$ and $S00E$ of Taft, El Centro and Northridge were considered in the direction of waves with 30 seconds duration. In order to achieve structural response at Peak Ground Acceleration (PGA), different earthquake striking time, Ts, (840.48sec for Taft, 842.08sec for El Centro and 840.58sec for Northridge) were considered. Therefore, all the earthquakes had their peak ground acceleration at the same time instant, i.e. Tx =844.20sec. Initially, the structure was assumed at rest. The response time interval for the duration of seismic as well as for random sea excitation was taken equal to the recorded ground motions time interval, i.e. 0.02 seconds. The chosen time interval yielded sufficient accuracy with the step-by-step integration scheme. The response quantities of interest are mean, standard deviation and peak values of top displacement, shear force at articulations and bending moment over the duration of earthquake and at the peak ground accelerations.

5. Effect of Seismic Sea Environment

Compliant structures located in seismic zones are expected to have large displacements. As such, serviceability and survivability of the structure is questionable. It has been observed that seismic shaking had resulted in significant increase in the structural responses. These responses in the presence of moderate sea are as discussed:

5.1. Effect on Heel Angle and Deck Displacement

The articulation of the tower is an important parameter for satisfactory performance and serviceability, especially in hostile sea environments. The higher the articulation, the larger shall be the top displacement. In the case of moderate random sea environment, the maximum rotation at the base articulation, as observed, was $3.52x10^{-3}$*rad*; whereas under Taft seismic sea environment, it was 0.0376*rad*, a 10.68 times increment. Upon comparing with El Centro and Northridge seismic sea environments, an increment of 14.46 and 17.50 times was observed respectively. The upper shaft too had followed the same trend as the lower shaft, but the responses are on higher side. The maximum upper shaft rotation as observed was $8.22x10^{-3}$*rad*, which is 2.3 times higher than the maximum rotation of the lower shaft under random sea environment. Whereas, the maximum rotation under El Centro seismic sea environment was 18.25 times higher with respect to random sea environment. Upon, comparing the upper shaft rotation with different seismic sea environments, the maximum rotations range from 0.0725*rad* (Taft) to 0.1500*rad* (El Centro), which is almost twice of each other, see Table (2).

Time histories of surge at top of the tower due to random and seismic sea excitations are shown in Figure (3). The time variation of the top displacement under random sea environment is almost negligible as compared to seismic sea responses. The average of the maximum value of surge in seismic sea environment was found to be 27.88*m*, which is 14.08 times higher than the maximum surge under random sea environment. The seismic response quickly diminishes as the earthquake is over restoring the steady state condition. Mean and standard deviation of top surge under random sea and seismic sea environments are tabulated in Table (3). In particular, top surge under El Centro seismic sea environment is 15.41 times than that of random sea environment. In all the seismic sea environments, standard deviation for surge varies from 4.370 (Taft seismic sea environment) to 6.73 (Northridge seismic sea environment).

Table 2. Comparative peak responses of the multi-articulated offshore tower.

Peak Responses	**Random Sea Environment**	**Seismic Sea Environment**		
		Taft 1952	**El Centro 1940**	**Northridge 1994**
Heel Angle (rad) • *Lower shaft*, $(?_1)$ • *Upper shaft*, $(?_2)$	 3.52×10^{-3} 8.22×10^{-3}	 0.0376 0.0725	 0.0509 0.1500	 0.0616 0.1028
Top Displacement (m)	1.98	18.40	30.52	34.72
Shear-Base Articulation (N)	$1.30 \times 10^{+6}$	$1.14 \times 10^{+7}$	$1.67 \times 10^{+7}$	$2.15 \times 10^{+7}$
Shear-Upper Articulation (N)	$1.79 \times 10^{+6}$	$1.56 \times 10^{+7}$	$3.80 \times 10^{+7}$	$2.92 \times 10^{+7}$
Note: Random Sea Environment (H_s = 6m, T_z = 12sec)				

Table 3. Comparative statistical responses of the multi-articulated offshore tower.

Response Quantity	**Random Sea Environment**		**Seismic Sea Environment**					
			Taft 1952		**El Centro 1940**		**Northridge 1994**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Heel Angle (rad) • *Lower Shaft*, $(?_1)$ • *Upper Shaft*, $(?_2)$	 -8.8×10^{-5} -1.3×10^{-4}	 1.2×10^{-3} 2.7×10^{-3}	 -6.4×10^{-5} -1.9×10^{-4}	 8.0×10^{-3} 0.014	 -4.4×10^{-5} 2.1×10^{-4}	 0.0113 0.0212	 -5.2×10^{-4} -9.4×10^{-4}	 0.0119 0.0213
Top Displacement (m)	-0.0517	0.6757	-0.0570	4.370	0.029	6.209	-0.346	6.7332
Shear Force • *Base Articulation* (N) • *Upper Articulation* (N)	 751.89 4709.74	 $3.9 \times 10^{+5}$ $6.3 \times 10^{+5}$	 -13.99 8796.37	 $1.3 \times 10^{+6}$ $2.5 \times 10^{+6}$	 -45091.7 3639.72	 $2.3 \times 10^{+6}$ $4.4 \times 10^{+6}$	 15551.3 21099.1	 $2.3 \times 10^{+6}$ $3.6 \times 10^{+6}$
Note: Random Sea Environment (H_s = 6m, T_z = 12sec)								

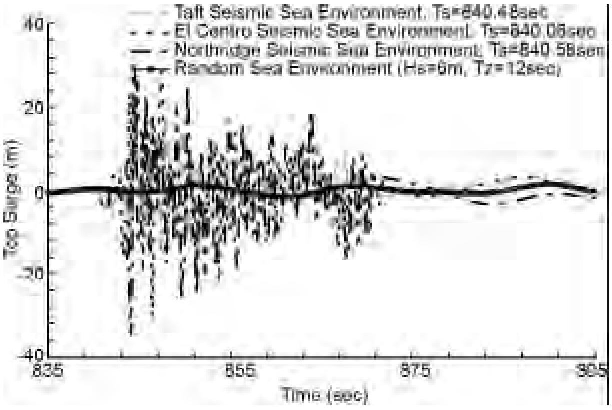


Figure 3. Time History of Top Surge.

5.2. Effect on Shear at Upper Articulation

Figure (4) shows the comparative power spectrum of shear force at the upper articulated joint. The foremost initial peak at 0.37*rad/sec* occurs at wave's modal frequency, clearly indicating that the wave forces due to 6.0*m*/12.0*sec* wave have significant energy. The high frequency energy content of the earthquakes are not attracted due to the compliant nature of the tower although the responses have increased manifolds. Higher shear spectral densities are observed in the upper articulation than the lower articulated joint, thereby, making it a critical joint. For comparative seismic shear at the articulations, peak values and the statistical values of interest are tabulated in Tables (2) and (3).

5.3. Instantaneous Response at Peak Ground Acceleration

Figure (5) shows the comparative variation (*Tx*= 844.20*sec*) of shear force under random and seismic sea environments at the *PGA's* of the earthquake time history. The presence of upper articulation had caused large variations in shear force at the two articulations. The variation is much higher in seismic sea environment. The variation in shear force under Taft and El Centro seismic sea environments are comparable while shear force under Northridge seismic sea environment is much higher. The average of peak base shear articulation under seismic sea environment is 12.91 times higher than that of random sea environment.

The corresponding instantaneous seismic bending moments along with the variation under random sea environment is shown in Figure (6). The presence of upper articulation reflects its contribution, i.e. reduction in the values of the bending moment. Likewise, seismic shear at upper articulation, at the

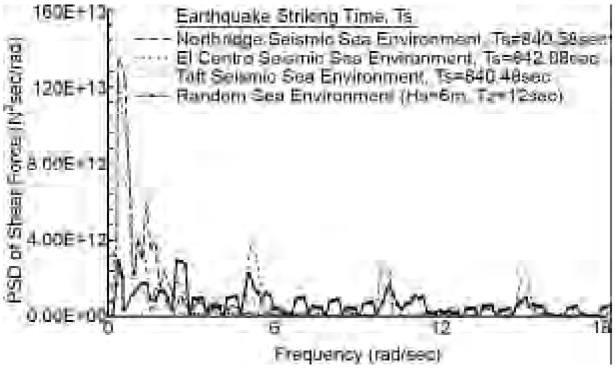


Figure 4. Spectral density of upper articulated joint.

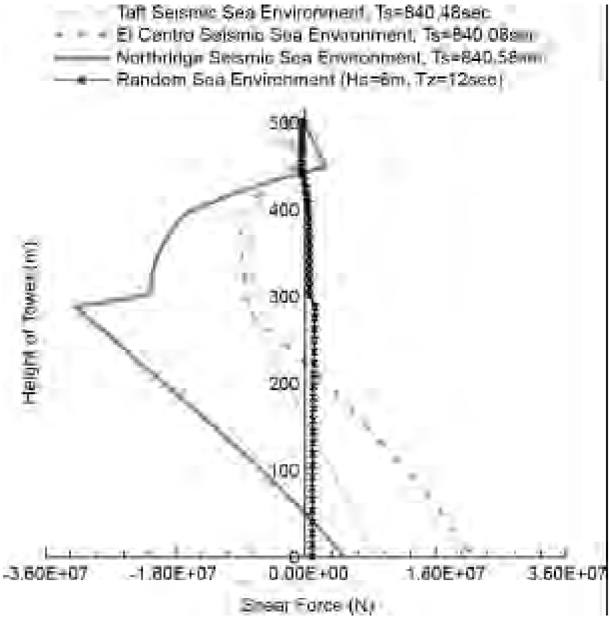


Figure 5. Seismic shear force at PGA (Tx=844.20sec).

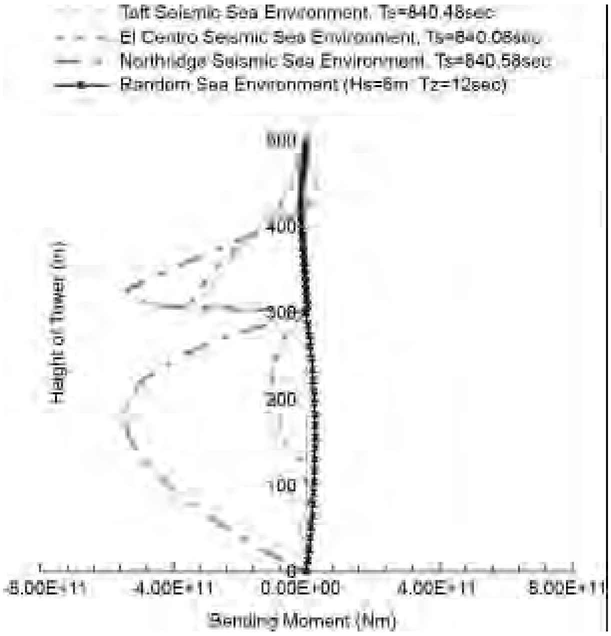


Figure 6. Seismic bending moment at PGA (Tx=844.20sec).

same time, had significantly increased but seismic shear at the bottom has reduced. Therefore, for a successful design of articulated offshore tower, especially in seismic zones, upper articulation should be able to sustain large seismic demands.

6. Conclusions

Multi-articulated offshore towers, if built in seismically active zones, had to withstand large seismic sea demands and therefore are susceptible to failure during earthquakes. Therefore, as part of seismic response studies, dynamic analysis were carried out in time domain for a 500*m* high multi-articulated offshore tower by employing three real Californian earthquakes. Following conclusions have been drawn:

- Owing to higher responses, the upper articulation is the critical joint for a multi-articulated offshore tower.
- The average horizontal excursion, for the model under consideration, has been found to be 14 times higher in seismically active zones.

References

1. Chakrabarti, S.K. and Cotter, D.C. (1980). "Transverse Motion of Articulated Tower", *J. of the Waterway Port Coastal and Ocean Division, ASCE*, **106**(1), 65-78.

2. Sellers, L.L. and Niedzwecki, J.M. (1992). "Response Characteristics of Multi-Articulated Offshore Towers", *Ocean Engineering*, **19**(1), 1-20.

3. Bar-Avi, P. and Benaroya, H. (1997). "Stochastic Response of a Two DOF Articulated Tower", *International Journal of Non-Linear Mechanics*, **32**(4), 639-655.

4. Kumar, D. and Datta, T.K. (2008). "Stochastic Response of Articulated Leg Platform in Probability Domain", Probabilistic Engineering Mechanics, **23**, 227-236.

5. McNeilly, C.C., Redwine, R.V., and Higgs, W.G. (2006). "Benguela-Belize Project Overview", OTC 178200, *Proc. of Offshore Technology Conference*, Houston, Texas, USA.

6. Foo, S.H.C. and Thompson, G.R. (1984). "Responses of Single Point Mooring Structure to Earthquake Excitation", *Proc. of International Conference on Offshore Mechanics and Arctic Engineering*, 373-391.

7. Ryu, C-S. and Yun, C-B. (1997). "Nonstationary Response Analysis of Offshore Guyed Tower Subjected to Earthquake Loading", *Journal of Engineering Structures*, **19**(1), 63-70.

8. Lina, H., Youngang, T., and Cong, YI. (2006). "Seismic Response Analysis of Articulated Tower Platform in the Still Water", China Offshore Platform, 03.

9. Islam, N. and Ahmad, S. (2003). "Random Wave Response of Double Pendulum Articulated Offshore Tower", *Proc. of International Conference on Offshore Mechanics and Arctic Engineering*, Cancum, Mexico, 489-498.

10. Islam, N. and Ahmad, S. (2006). "Earthquake Response of Articulated Offshore Tower", *J. of European Earthquake Engineering*, **1**, 48-58.

11. Wu, J. and Chen, C. (2007). "Forced Vibration Analysis of an Offshore Tower Carrying an Eccentric Tip Mass with Rotary Inertia due to Support Excitation", *J. of Ocean Engineering*, **34**(8), 1235-1244.

12. Chandrasekaran, S. and Gaurav (2008). "Offshore Triangular TLP Earthquake Motion Analysis under Distinctly High Sea Waves", *International Journal of Ship and Offshore Structures*, (Taylor and Francis), **3**(3), 173-184.

13. Chakrabarti, S.K. (1971). "Discussion of Dynamics of Single Point Moorings in Deep Water", *Journal of the Waterways, Harbors and Coastal Engineering Division, ASCE*, **97**(3), 588-590.