CHALLENGE JOURNAL OF STRUCTURAL MECHANICS 1 (4) (2015) 198–201

Challenge Journal of Structural Mechanics

Seismic analysis of offshore wind turbine including fluid-structure-soil interaction

Kemal Hacıefendioğlu *, Fahri Birinci

Department of Civil Engineering, Ondokuz Mayıs University, 55139 Samsun, Turkey

ABSTRACT

This paper presents the seismic response analysis of offshore wind turbines subjected to multi-support seismic excitation by using a three dimensional numerical finite element model considering viscous boundaries. The sea water-offshore wind turbine-soil interaction system is modeled by the Lagrangian (displacement-based) fluid and solid-quadrilateral-isoparametric finite elements. The research conducts a parametric study to estimate the effects of different foundation soil types on the seismic behavior of the offshore wind turbine coupled interaction system. The results obtained for different cases are compared with each other.

ARTICLE INFO

Article history:
Received 15 May 2015
Accepted 21 July 2015

Keywords:
Offshore wind turbine
Ice sheet
Fluid-structure interaction
Seismic analysis
Lagrangian approach

1. Introduction

In recent years, because of spending too much energy in the world, it needs additional energy. Therefore, the wind turbine industry has developed rapidly for sustainable energy production. In most regions of the world, wind turbines are built on the active earthquake zone. Therefore, in order to adequately design, operate, and maintain wind turbines, in particular, for sites with high peak ground acceleration, it seems necessary to take into account earthquakes.

Seismic analysis of wind turbine subjected to earthquake ground motion has been studied and published by only a limited number of researchers. Bazeos et al. (2002) presented the load bearing capacity and the seismic behavior of a prototype steel tower for a 450 kW wind turbine with a horizontal power transmission axle. The structure was analyzed for static and seismic loads representing the effects of gravity, the operational and survival aerodynamic conditions, and possible site-dependent seismic motions by using the finite element method.

Witcher (2005) used an alternative approach to undertake the calculation of seismic response of wind turbine during earthquake ground motion by using the computer software. The software can be used to compute the combined wind and earthquake loading of a wind turbine given a definition of the external conditions for an appropriate series of load cases. Maißer and Zhao (2006) investigated the dynamic responses of wind turbine towers to seismic excitations in time domain, considering soil structure interaction. The soil structure interaction was represented by a frequency-independent discrete parameter model approximately. The governing motion equations were derived by the application of Lagrange formalism including Lagrange multipliers.

The current research investigates the effects of different soil properties on the stochastic response of offshore wind turbine for random seismic excitation. All the numerical analyses are performed using computer program ANSYS (2003).

2. Lagrange Approach for Fluid Systems

The formulation of the fluid system is presented according to the Lagrangian approach (Wilson and Khalvati, 1983). In this approach, fluid is assumed to be linearly elastic and irrotational. Also, the fluid is assumed to be non-flowing and inviscid (that is, viscosity causes no dissipative effects). For this fluid, the relation between pressure and volumetric strain is given by

* *Corresponding author.* Tel.: +90-362-3121919 ; E-mail address: hckemal@omu.edu.tr (K. Hacıefendioğlu)
ISSN: 2149-8024 / DOI: http://dx.doi.org/10.20528/cjsmec.2015.07.027

$$\begin{Bmatrix} P \\ P_x \\ P_y \\ P_z \end{Bmatrix} = \begin{bmatrix} C_{11} & 0 & 0 & 0 \\ 0 & C_{22} & 0 & 0 \\ 0 & 0 & C_{33} & 0 \\ 0 & 0 & 0 & C_{44} \end{bmatrix} x \begin{Bmatrix} \varepsilon_v \\ W_x \\ W_y \\ W_z \end{Bmatrix} , \quad (1)$$

where P, C_{11} and ε_v are the pressures which are equal to mean stresses, the bulk modulus and volumetric strains of fluid, respectively. In Eq. (1), P_x, P_y, P_z are the rotational stresses; C_{22}, C_{33}, C_{44} are the constraint parameters and w_x, w_y and w_z are the rotations about the Cartesian axis x, y and z, respectively.

In this study, the equations of motion of the fluid system are obtained using energy principles. Using the finite element approximation, the total strain energy of the fluid system may be written as,

$$\pi = \frac{1}{2} u_f^T K_f u_f , \quad (2)$$

where K_f and u_f are the stiffness matrix and the nodal displacement vector of fluid system, respectively. K_f is derived by summing stiffness matrices of the fluid elements as follows:

$$K_f = \sum K_f^e \quad , \quad K_f^e = \int_v B_f^{eT} C_f B_f^e dV^e , \quad (3)$$

where C_f is elasticity matrix consisting of diagonal terms in Eq. (1). B_f^e is strain-displacement matrix of the fluid element.

An important behavior of fluid systems is the ability to displace without a change in volume. The increase in the potential energy of the system due to the free surface motion can be written as,

$$\pi_s = \frac{1}{2} u_{sf}^T S_f u_{sf} , \quad (4)$$

where u_{sf} and S_f are vertical nodal displacement vector and stiffness matrix of the free surface of the fluid system, respectively.

$$S_f = \sum S_f^e \quad , \quad S_f^e = \rho_f g \int_A \overline{h}_s^T \overline{h}_s \, dA^e , \quad (5)$$

where $\overline{h}_s$ is a vector consisting of interpolation functions of the free surface fluid element, ρ_f and g are mass density of the fluid and acceleration due to gravity, respectively.

Finally, the kinetic energy of the fluid system must be considered to complete the energy contributions. This energy is given by,

$$T = \frac{1}{2} \dot{u}_f^T M_f \dot{u}_f , \quad (6)$$

where M_f and $\dot{u}_f$ are the mass matrix and the nodal velocity vector of the fluid system, respectively (Clough and Penzien, 1993). M_f is also obtained by summing the mass matrices of the fluid elements in the following:

$$M_f = \sum M_f^e \quad , \quad M_f^e = \rho_f \int_V \overline{H}^T \overline{H} dV^e , \quad (7)$$

where $\overline{H}$ is a matrix consisting of interpolation functions of the fluid element.

If Eqs. (2), (4) and (6) are substituted into Lagrange's equations, the equation of motion of the fluid system can be obtained as follows,

$$M_f \ddot{u}_f + K_f^* u_f = R_f , \quad (8)$$

where K_f^* , $\ddot{u}_f$, and R_f are system stiffness matrix including the free surface stiffness, nodal acceleration vector and nodal force vector, respectively (Bathe, 1996).

3. Stochastic Formulation

Since the formulation of the stochastic dynamic analysis of structural systems has been well known for many years, only the final equations will be given in this study. Detailed formulations for stochastic dynamic analysis are given in references (Lin, 1967; Yang, 1986; Manolis and Koliopoulas, 2001). One of the most important factors in stochastic analysis is the power spectral density function. If the power spectral density function of input process is known, the power spectral density function of output process can be determined easily. Filtered white noise model is generally used as power spectral density function for the modeling of ground motion simulation. Cross power spectral density function can be determined by using the equation of motion of the system under the ground motion as;

$$S_{ij}(\omega) = S_{\ddot{u}_g}(\omega) \sum_{r=1}^{N} \sum_{s=1}^{N} \psi_{ir} \psi_{js} H_{ir}(\omega) H_{js}^*(\omega) , \quad (9)$$

where $S_{\ddot{u}g}(\omega)$ represents the power spectral density function of ground motion, ω represents the frequency, $H(\omega)$ represents the frequency response function, N is the number of modes which are considered to contribute to the response, ψ_{ir} is the contribution of the rth mode to $u_j(t)$ displacement and * denotes the complex conjugate. For i=j, Eq. (9) gives the power spectral density function of the ith displacement.

4. Ground Motion Model

Ground motions are known to highly nonstationary in nature (both in amplitude and frequency content) and this has a huge impact on the stochastic response. Since the primary objective of this study is to perform a parametrical study with the ice cover effects on the response of offshore wind turbine subjected to stochastic seismic excitation, the non-stationary ground motion is not considered.

The power spectral density function of ground acceleration for stationary ground motion is assumed to be of the form of filtered white noise ground motion model originally proposed by Kanai (1957)–Tajimi (1960) and modified by Clough and Penzien (1993),

$$S_{\ddot{u}_g}(\omega) = S_0 \left(\frac{\omega_g^4 + 4\xi_g^2 \omega_g^2 \omega^2}{\left(\omega_g^4 - \omega^2\right)^2 + 4\xi_g^2 \omega_g^2 \omega^2} \right) \cdot \left(\frac{\omega^4}{\left(\omega_f^4 - \omega^2\right)^2 + 4\xi_f^2 \omega_f^2 \omega^2} \right), \quad (10)$$

where, ω_g and ξ_g are the resonant frequency and damping ratio of the first filter; ω_f and ξ_f are those of the second filter; and S_0 is the spectrum of the white-noise bedrock acceleration.

Power spectral density function of the Kocaeli earthquake for firm soil type is shown in Fig. 1. The calculated intensity parameter value for firm soil type is, S_0(firm)=0.00103 m^2/s^3. Filter parameter values (ω_g, ξ_g, ω_f, ξ_f) proposed by Der Kiureghian and Nevenhofer (1991) are utilized as ω_g=15.0 rad/s, ξ_g=0.6, ω_f=1.5 rad/s, and ξ_f=0.6.

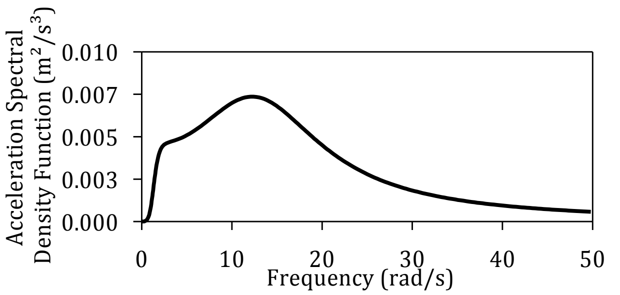

Fig. 1. Power spectral density function for the Kocaeli earthquake.

5. Application

The offshore wind turbine, water in the sea and soil was assumed to behave linear elastic, isotropic and homogeneous. Therefore, a non-linear phenomenon such as water cavitation was not included in the study. To evaluate the stochastic response of the coupled system, the material properties of the wind turbine body, sea water and soil media used in the analyses are given in Table 1. In addition, the average thicknesses of the wind turbine are shown in Fig. 2. The mass of the nacelle was taken into account as 130,000 kg.

Table 1. Material properties of considered coupled system.

Material	Elasticity Modulus (kN/m^2)	Poisson's Ratio	Mass per unit Vol. (kg/m^3)
Turbine	2.06x10^7	0.30	7800
Soil type (S1)	2.00x10^6	0.30	2000
Soil type (S2)	3.00x10^5	0.35	1900
Soil type (S3)	5.00x10^4	0.40	1800
Sea water	2.07x10^6	-	1000

In this research, the stochastic responses of the fluid-structure-soil interaction system of the offshore wind turbine are estimated by using a three dimensional finite element model based on Lagrangian approach (Fig. 3). In the Lagrangian approach, displacements are selected as the variables in both fluid and structure domains (Calayır et al., 1996; Olson et al., 1983). The formulation of the fluid system is presented according to the Lagrangian approach (Wilson and Khalvati, 1983). In this approach, fluid is assumed to be linearly elastic, inviscid and irrotational. The soil media is represented by solid elements; the wind tower and sea water are represented by shell and fluid elements in the finite element model, respectively. While SHELL63 element is used to model the wind turbine, soil media is modeled using SOLID45 elements; FLUID80 element is used to model the sea water media. At the sea water-wind turbine and sea water-soil, the length of the coupling element is chosen as 0.001 m. The main objective of the couplings is to hold equal the displacements between two reciprocal nodes. In this study, viscous boundary method developed by Lysmer and Kuhlemeyer (1969) is considered in three dimensions. These viscous boundaries can be used with the finite element mesh as shown in Fig. 3.

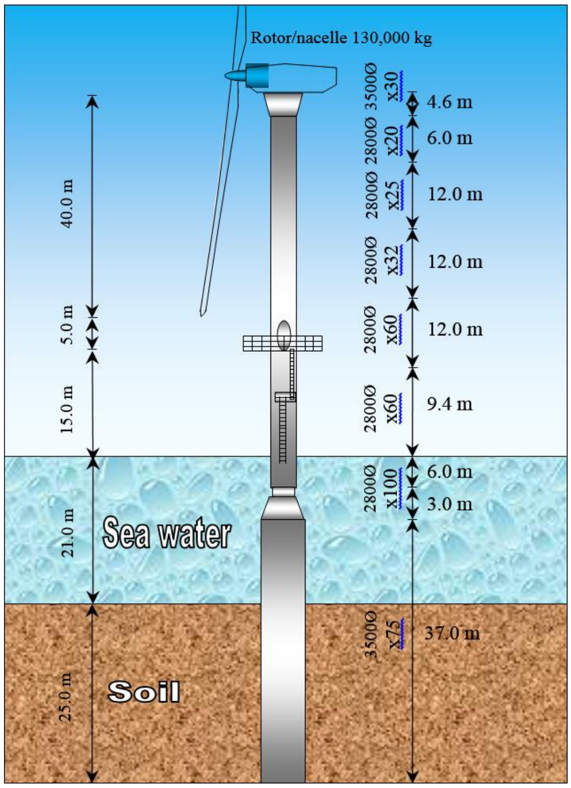

Fig. 2. Main dimensions of the offshore wind turbine.

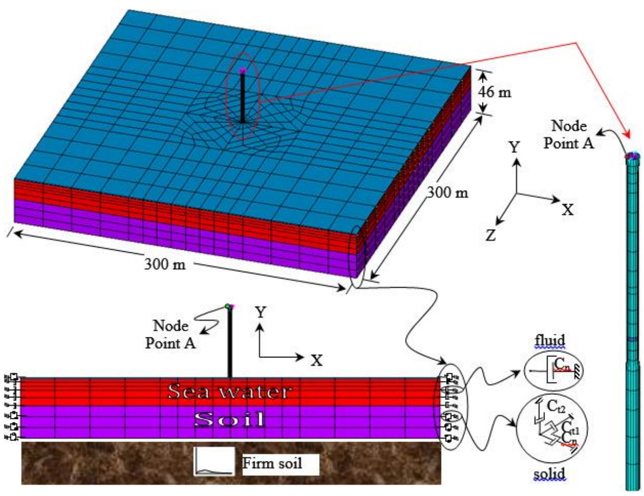

Fig. 3. Finite element model of the sea water-wind turbine-soil interaction system for different soil conditions.

6. Results

The effects of the foundation soil properties on the stochastic response of the offshore wind turbine are illustrated in Figs. 4-5 by using three soil types (Table 1). In this section, all the support site conditions have firm soil (FF). For this purpose, the displacement power spectral density (PSD) values for these soil types, at point A, depending on the frequency ranging from 0.0 to 1.4 Hz, is shown in Fig. 4. It is concluded from the figure that the displacement values increase as the soil gets softer. The same comments can be made for the one standard deviation (1σ) of the Von Misses stress responses (N/m^2) due to the different soil types on the offshore wind turbine as illustrated in Fig. 5. The maximum stresses for S1 and S3 soil types occur in the same regions on the offshore wind turbine. Whereas the maximum stress values due to S2 soil type occur in the different region on the offshore wind turbine.

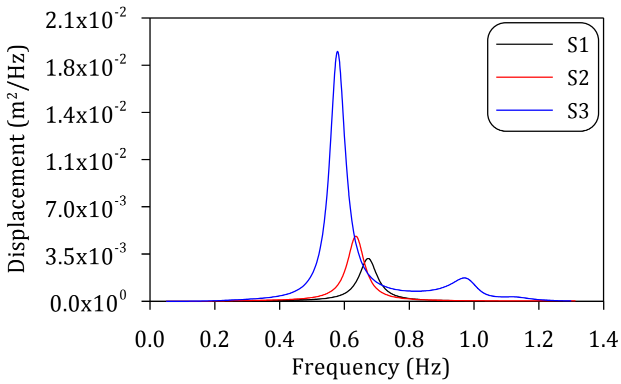

Fig. 4. The displacement power spectral density values at point A for the different soil types.

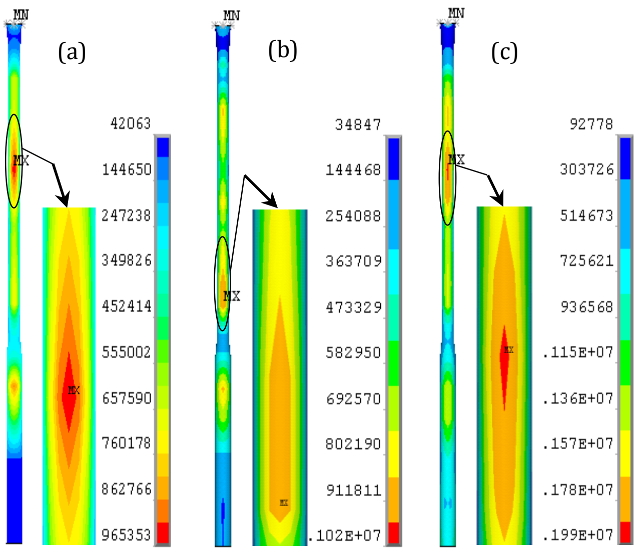

Fig. 5. 1σ Von Misses stress contours for (a) S1, (b) S2 and S3 soil types.

7. Conclusions

This study investigates the stochastic response of an offshore wind turbine under the random seismic excitation. The parametric analyses were carried out by considering the structure-sea water-soil interaction. The results for the coupled interaction finite element system have been modeled by using the computer software called ANSYS.

The stochastic response of the offshore wind turbine including the structure-sea water-soil interaction during random seismic excitation is considerably affected by the different foundation soil properties. The results show that the values of the stochastic response of the coupled system increases as soil gets softer.

References

ANSYS (2003). Swanson Analysis System, USA.

Bathe KJ (1996). Finite Element Procedures in Engineering Analysis. Prentice-Hall Inc., Englewood Cliffs, NJ.

Bazeos N, Hatzigeorgiou GD, Hondros ID, Karamaneas H, Karabalis DL, Beskos DE (2002). Static seismic and stability analyses of a prototype wind turbine steel tower. *Engineering structures*, 24(8), 1015-1025.

Calayır Y, Dumanoğlu AA, Bayraktar A (1996). Earthquake analysis of gravity dam–reservoir systems using the Eulerian and Lagrangian approaches. *Computer and* Structures, 59(5), 877–90.

Clough RW, Penzien J (1993). Dynamics of Structures. 2nd edition, McGraw-Hill, Singapore.

Der Kiureghian A, Neuenhofer A (1991). A response spectrum method for multiple-support seismic excitations. Report No. UCB/EERC-91/08, Berkeley (CA): Earthquake Engineering Research Center, College of Engineering, University of California, California.

Kanai K (1957). Semi-empirical formula for the seismic characteristics of the ground. *Bulletin* of the *Earthquake Research Institute,* 35, 307-325.

Lin YK (1967). Probabilistic Theory of Structural Dynamics. McGraw Hill, New York.

Lysmer J, Kuhlemeyer RL (1969). Finite dynamic model for infinite media. *ASCE Journal* of *the Engineering Mechanics Division*, 95, 859-877.

Maißer P, Zhao X (2006). Seismic response analysis of wind turbine towers including soil-structure interaction. *Proceedings of the Institution of Mechanical Engineers, Part K, Journal of Multi-body Dynamics,* 220(1), 53-61.

Manolis GD, Koliopoulos PK (2001). Stochastic Structural Dynamics in Earthquake Engineering. WIT Press, Southampton.

Olson LG, Bathe KJ (1983). A study of displacement-based fluid finite elements for calculating frequencies of fluid and fluid-structure systems. *Nuclear Engineering and Design*, 76(2), 137–51.

Tajimi H (1960). A statistical method for determining the maximum response of a building structure during an earthquake. *Proceedings 2nd World Conference Earthquake Engineering*, Tokyo and Kyoto, Japan.

Wilson EL, Khalvati M (1983). Finite elements for the dynamic analysis of fluid-solid systems. *International Journal for Numerical Methods in Engineering*, 19(11), 1657-1668.

Witcher D (2005). Seismic analysis of wind turbines in the time domain. *Wind Energy*, 8(1), 81-91.

Yang CY (1986). Random Vibration of Structures. John Wiley and Sons Inc., New York.