Engineering Structures 33 (2011) 1607–1616

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Dynamic response analysis of an offshore platform due to seismic motions

Min-su Park [a], Weoncheol Koo [a,*], Kenji Kawano [b]

[a] School of Naval Architecture and Ocean Engineering, University of Ulsan, Republic of Korea

[b] Department of Ocean and Civil Engineering, Kagoshima University, Japan

ARTICLE INFO

Article history:
Received 28 July 2010
Received in revised form
26 January 2011
Accepted 29 January 2011
Available online 10 March 2011

Keywords:
Modal analysis
Substructure method
Impedance function
Monte Carlo simulation method
Reliability evaluation
Seismic motion

ABSTRACT

A three-dimensional (3D) numerical model for dynamic response analysis of seismic-induced motions is developed using the modal analysis and substructure methods. The developed model and an impedance function method are applied to an offshore platform with a pile–soil foundation system. The Newmark β method is used as a time integration scheme. The displacement and bending stresses at selective nodal points on the structure are computed for various maximum seismic accelerations and the shear-wave velocities of soil. Using a reliability index obtained by the Monte Carlo Simulation method, we successfully performed a reliability evaluation at the critical points of the structure for various seismic motions and soil conditions.

1. Introduction

It is of great importance to utilize ocean spaces and marine renewable energies, as land-based resources are increasingly depleted. Ocean structures such as offshore platforms and basins may provide opportunities for the development and utilization of ocean resources. Incident wave is a primary concern for the safety of structure and an array of cylinders as a common shape of offshore platform is used to predict the wave excitation forces [1]. In active seismic zones near the Pacific Rim, however, seismic-induced ground motion is one of the most critical excitation loads to carefully evaluate when ensuring that platforms retain proper seismic resistance.

Several studies have been carried out on the seismic responses of offshore structures. A zero mean ergodic Gaussian process of finite duration [2] or Kanai–Tajimi power spectrum [3–5] was used to determine horizontal ground acceleration due to earthquakes. Two primary techniques can be used to analyze the structure–foundation system and its characteristics, direct and substructure methods, both of which are outlined by Wolf [6,7]. Aydinoglu [8,9] developed mathematical formulations for both methods. Three sub-schemes have been developed for the dynamic interactions of soil and pile groups on the seabed: the equivalent single pile scheme, the elasticity scheme, and the general three-dimensional load transfer scheme. References for these methods can be found in Park et al. [10].

Loads on the foundation due to earthquakes involve uncertainties when the dynamic characteristics are determined using time histories of the data [11]. Thus, for accurate dynamic structure response, uncertain parameters such as seismic motions and shear-wave velocities of soil may be considered using the Monte Carlo Simulation (MCS) method, which is an efficient way to detect uncertainties. Several studies of jacket structures have been reported regarding reliability evaluation of uncertain seismic motions, e.g., [12–15]. In particular, the use of the MCS method in a nonlinear system including seismic motions is necessary to calculate the reliability index for the evaluation.

In this study, using modal analysis a three-dimensional (3D) numerical model is developed for the dynamic response induced by various standardized maximum seismic accelerations measured in Japan. The newly developed model was applied to a bottom-mounted offshore platform with a pile–soil foundation system. The interactions of the structure and foundation systems were also considered using the substructure method. The Newmark β method as a time integration scheme for 3D cases, which was formulated by Park et al. [10], was applied to the present case. The offshore platform considered in this study is illustrated in Fig. 1. The platform consists of two structural subsystems; the superstructure and the pile–soil foundation subsystems, which are connected at the nodal points between the pile heads of the foundation and the bottom of the superstructure. The lower part of the superstructure is a truss-type structure, and the upper part

* Corresponding author. Tel.: +82 59 259 2767; fax: +82 52 259 2836.
E-mail address: kwc1969@yahoo.com (W. Koo).

0141-0296/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engstruct.2011.01.030

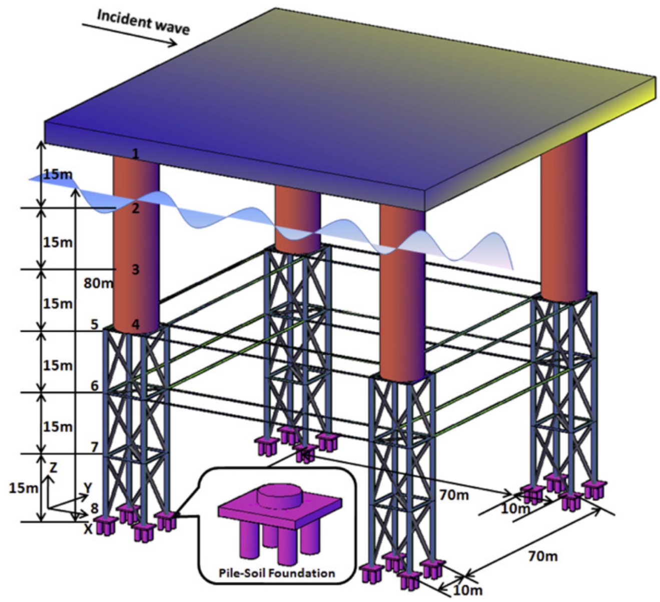

Fig. 1. The present offshore platform with a pile–soil foundation system.

consists of four buoyancy-type columns (BTC) that reduce the reaction forces from the basement.

A 3D load transfer scheme was used for accurate calculation of dynamic response including the interactions of the structure–foundation system. Using finite cylindrical elements, the equation of motion was solved to determine the superstructure's response, and the impedance function method was employed to analyze the pile–soil foundation system. From a comparison of seismic-induced body responses, the significance of seismic effects will be addressed. The effects of uncertain seismic motions and the soil conditions on the dynamic response will also be evaluated in the analysis of the reliability index.

2. Mathematical formulations

2.1. The governing equation of motion

The motion behavior of a platform located in a seismic zone is governed by the dominant seismic frequency and the first mode of the natural frequency of the structure. Using time histories of seismic forces, a modal analysis can be performed to determine the dynamic structural response.

In this study, dynamic response analysis for an ideal three-dimensional framed-structure with a pile–soil foundation system induced by seismic motions is performed. Fig. 1 shows an overview of the bottom foundation system, as well as the BTC in the upper structure. For mathematical modeling of the current structure, a Cartesian coordinate system was chosen such that the origin is located at a point on the sea bottom projected from the left corner of the deck plate. x is positive to the right and z is positive in the upward direction. For numerical calculation, the platform is composed of 266 discrete cylindrical elements and 96 nodal points. Eight nodal points on the superstructure, as indicated in Fig. 1, were selected to calculate the respective displacement and the bending stress against seismic motions. The second and eighth nodal points, located near the mean water level and the structure bottom, respectively were specified as critical points for structural safety. The platform consists of a framed-structure and a pile–soil foundation subsystem and has a connection at the eighth nodal point between the pile heads of the foundation and the bottom of the superstructure. Since the two subsystems interact by transferring the displacement and dynamic forces at the pile heads and the truss bases, the governing equation of motion for the entire structure can be formulated as:

$$\begin{bmatrix} [M_{aa}] & [M_{ab}] \\ [M_{ba}] & [M_{bb}] \end{bmatrix} \begin{Bmatrix} \ddot{u}_a \\ \ddot{u}_b \end{Bmatrix} + \begin{bmatrix} [C_{aa}] & [C_{ab}] \\ [C_{ba}] & [C_{bb}] \end{bmatrix} \begin{Bmatrix} \dot{u}_a \\ \dot{u}_b \end{Bmatrix} + \begin{bmatrix} [K_{aa}] & [K_{ab}] \\ [K_{ba}] & [K_{bb}] \end{bmatrix} \begin{Bmatrix} u_a \\ u_b \end{Bmatrix} = \begin{Bmatrix} \{F_a\} \\ \{F_b\} \end{Bmatrix} \tag{1}$$

where the subscripts 'a' and 'b' denote the unconstrained nodal point on the superstructure and the point connected to the pile–soil foundation system, respectively. $[M]$, $[C]$ and $[K]$ represent the mass matrix, the damping coefficient matrix, and the stiffness matrix of the structure, respectively. The vector $\{F_a\}$ is the external force acting on the superstructure, $\{F_b\}$ is the reaction force caused by the interaction of the structure–foundation system from seismic motions, $\{u_a\}$ is the displacement of the superstructure, and $\{u_b\}$ is the displacement of the eighth nodal point. The external force on the superstructure can be obtained from the following equation.

$$\{F_a\} = [C_M]\{\dot{v}_a\} - [C_m]\{\ddot{u}_a\} + [C_D]\{|\dot{v}_a - \dot{u}_a|(\dot{v}_a - \dot{u}_a)\} \tag{2}$$

where

$$[C_M] = \begin{bmatrix} \ddots \; \rho C_M V \; \ddots \end{bmatrix}$$

$$[C_D] = \begin{bmatrix} \ddots \; \rho C_D \frac{A}{2} \; \ddots \end{bmatrix}.$$

The matrices $[C_M]$ and $[C_D]$ represent the inertia and drag coefficients, respectively, and the added mass coefficient $C_m = C_M - 1$ and $\ddot{v}_a$ and $\dot{v}_a$ denote the acceleration and velocity of water particles at the unconstrained nodal points, respectively. ρ represents the water density, V is the enclosed volume and A is the projected area in the direction of flow. For convenient and efficient analysis, a linearized drag force obtained by the least square method was applied to the equation of motion. Assuming that the relative velocity between the water particles and the structure is a zero mean Gaussian process, the equation of motion using Eq. (2) can be rearranged as:

$$\begin{bmatrix} \left[\tilde{M}_{aa}\right] & [M_{ab}] \\ \left[\tilde{M}_{ba}\right] & [M_{bb}] \end{bmatrix} \begin{Bmatrix} \ddot{u}_a \\ \ddot{u}_b \end{Bmatrix} + \begin{bmatrix} \left[\tilde{C}_{aa}\right] & [C_{ab}] \\ \left[\tilde{C}_{ba}\right] & [C_{bb}] \end{bmatrix} \begin{Bmatrix} \dot{u}_a \\ \dot{u}_b \end{Bmatrix} + \begin{bmatrix} [K_{aa}] & [K_{ab}] \\ [K_{ba}] & [K_{bb}] \end{bmatrix} \begin{Bmatrix} u_a \\ u_b \end{Bmatrix} = \begin{bmatrix} [C_M] & [C_D] \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} \ddot{v}_a \\ \dot{v}_a \end{Bmatrix} + \begin{Bmatrix} 0 \\ \{F_b\} \end{Bmatrix} \tag{3}$$

where

$$\left[\tilde{M}\right] = [M] + [C_m]$$

$$\left[\tilde{C}\right] = [C] + [C_D].$$

From Eq. (3), it is expected that the dynamic vibration due to inertia force and the quasi-static displacement caused by the pile–soil foundation system would be located in the superstructure system. They are given by:

$$\begin{Bmatrix} \{u_a\} \\ \{u_b\} \end{Bmatrix} = \begin{bmatrix} [I] & [L] \\ 0 & [I] \end{bmatrix} \begin{Bmatrix} \{u_a^c\} \\ \{u_b\} \end{Bmatrix} \tag{4}$$

where

$$[L] = -[K_{aa}]^{-1}[K_{ab}]$$

u_a^c is the displacement due to the inertia force in the fixed foundation system, and $[I]$ is the unitary matrix.