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Induced water pressure profiles due to seismic motions

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ABSTRACT

About 90% of all natural earthquakes have epicenters in offshore areas and may cause damage to subsea and floating structures. These excitations can have effects on the performance of facilities installed on the seabed, like foundations, pipelines and subsea equipment for the oil industry. Several studies on this subject have been carried out to show the importance of seaquake analyses and their effects have been highlighted. In this paper the boundary element method is used to analyze the influence that some parameters, involved in this kind of problems, have on the dynamic response of marine waters under the incidence of theoretical seismic events. This method takes advantage of the elastodynamic Green's functions and, after the application of boundary conditions, a Fredholm system of integral equations is achieved and solved in frequency domain. Results in time domain are also obtained by applying a DFT algorithm. Flat and non-flat seabed configurations excited for normal and oblique incidence of P and S waves are considered. Pressure profiles through water depth are provided and synthetic seismograms of pressure are also shown. Amplifications of water pressures are emphasized.

1. Introduction

About 90% of all natural earthquakes have epicenters in offshore areas [1]. Seaquakes are characterized by the propagation of vertical earthquake motions on the sea floor as a compression wave and are reported to cause damage to ships and their effect on floating structures is a matter of great concern [2]. When the seabed is vibrating due to seaquake, the compression waves propagate into seawater on account of compressibility of water. An analytical approach that can predict the dynamic response of a flexible circular floating island subjected to seaquakes was studied by Tanaka et al. [3], where the floating island was modeled as an elastic circular plate, and the anchor system is considered to be composed of tension-legs. A linear potential flow theory applied to flexible floating island subjected to wind-waves and seaquakes was presented in [4], here the hydrodynamic pressure generated on the bottom surface of the island was obtained in closed form. The non-linear transient response of floating platforms to seaquake-induced excitation was studied by Arockiasamy et al. [5], where cavitation effects were considered.

Ye [6] showed that under strong seismic loading, the surface region of seabed foundation could liquefy and also demonstrated that the Young's modulus of seabed foundation has significant effect on the seismic response. Liquefaction produced by waves at near shore areas was investigated using a marine geotechnical point of view [7]. Repeated loads from seaquakes cause softening of the clayey seabed foundation of offshore structures [8]. Special studies on design considerations for marine structures situated on sand deposits have shown the potential for instability caused by the development of excess pore pressure as a result of wave loading [9]. Liquefaction of seabed under seismic loading governs the overall stability of submarine pipeline [10,11].

A special boundary method for earthquake-induced hydrodynamic pressures on rigid axisymmetric offshore structures, including both the water compressibility and seabed flexibility, was presented by Avilés and Li [12]. A boundary integral equation was derived assuming that the seabed is a semiinfinite homogeneous elastic solid in order to analyze the seaquake-induced hydrodynamic pressure acting on the floating structure [2]. Boundary integral equations have been also used to calculate the hydrodynamic pressure caused by seaquake in layered media [13], and for three dimensional cases in [14]. Recently, the boundary element method and the discrete wave number method have been used to determine pressures near the interface of fluid–solid models [15,16].

Autonomous data-acquisition system using ocean bottom seismometer with hydrophones was used to record seismic and pressure signals generated by earthquakes and tsunamis [1]. Moreover, test deployments of seismic instruments have been successfully carried out in shallow water and full ocean depth by Minshull et al. [17].

This paper uses the boundary element method (BEM) to calculate the seismic profile through water depth due to the incidence of P and S waves on the seabed. Wave amplifications due to the configuration of the sea bottom are highlighted. Our formulation can be considered as a numerical implementation of Huygens' principle in which the diffracted waves are constructed at the boundary from which they are radiated. Thus, mathematically it is fully equivalent to the classical Somigliana's representation theorem. Our results are compared with those previously published. In the following paragraphs a brief explanation of the BEM applied to sea bottom subjected to seismic motions is given.

2. Formulation of the method

Consider the movement of an elastic solid, homogeneous and isotropic Ω in volume delimited by the boundary Γ, subjected to body forces $b_i(\xi, t)$ and zero initial conditions. Introducing fictitious

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sources of density $\phi_i(\xi, t)$ on Γ, the total fields of displacements and tractions can be written as Banerjee and Butterfield [18]:

$$\begin{aligned} u_j(x,t) &= \int_\Gamma G_{ij}(x,\xi) * \phi_i(\xi,t) d\Gamma_\xi + \int_\Omega G_{ij}(x,\xi) * b_i(\xi,t) d\Omega_\xi + u_j^o(x,t) \\ t_j(x,t) &= \int_\Gamma T_{ij}(x,\xi) * \phi_i(\xi,t) d\Gamma_\xi + \int_\Omega T_{ij}(x,\xi) * b_i(\xi,t) d\Omega_\xi + t_j^o(x,t) \end{aligned} \tag{1}$$

where $u_j^o(x, t)$ and $t_j^o(x, t)$ are free terms depending on the type of elastic waves impinging on the body, for this study is the occurrence of P and S waves. The symbol (*) means the convolution integral in the time domain, $x = \{x_1, x_3\}$. $G_{ij}(x, \xi)$ and $T_{ij}(x, \xi)$ are the Green's functions for displacements and tractions, respectively, which can be found in Section 3.

For Eq. (1) it is accepted that these boundary integrals are valid in the sense of the Cauchy principal value. Then, if allowed to the point x to move closer to the boundary Γ from inside, then Eq. (1) become the following boundary equations:

$$\begin{aligned} u_j(x,t) &= \int_\Gamma G_{ij}(x,\xi) * \phi_i(\xi,t) d\Gamma_\xi + \int_\Omega G_{ij}(x,\xi) * b_i(\xi,t) d\Omega_\xi + u_j^o(x,t) \\ t_j(x,t) &= \frac{1}{2}\phi_j(x,t)\delta_{ij} \int_\Gamma T_{ij}(x,\xi) * \phi_i(\xi,t) d\Gamma_\xi + \int_\Omega T_{ij}(x,\xi) * b_i(\xi,t) d\Omega_\xi + t_j^o(x,t) \end{aligned} \tag{2}$$

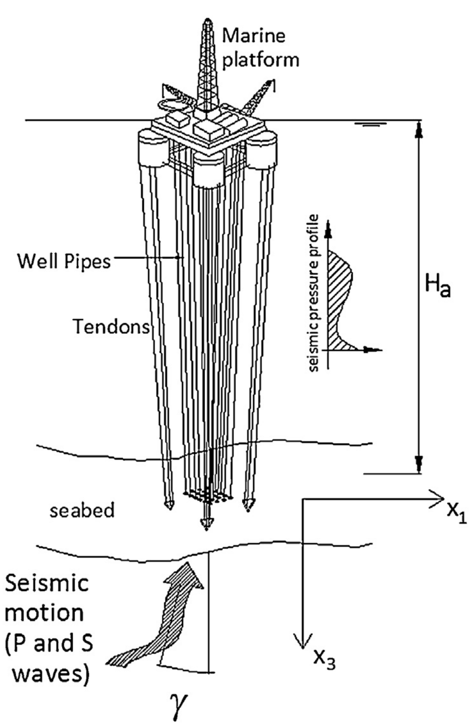

Fig. 1. Offshore structure under the incidence of seismic motions.

where δ_{ij} is Kronecker delta.

Transforming the problem to the frequency domain and accepting that the incidence wave has harmonic dependence with time, of the type $e^{i\omega t}$ (*i.e.* $u_j(x, t) = u_j(x, \omega)e^{i\omega t}$)), where ω is the circular frequency and "*i*" is the imaginary unit. Then, the displacements and tractions can be expressed as:

$$\begin{aligned} u_j(x,\omega) &= \int_\Gamma G_{ij}(x,\xi,\omega)\phi_i(\xi,\omega) d\Gamma_\xi + \int_\Omega G_{ij}(x,\xi,\omega) b_i(\xi,\omega) d\Omega_\xi + u_j^o(x,\omega) \\ t_j(x,\omega) &= \frac{1}{2}\phi_j(x,\omega)\delta_{ij} \int_\Gamma T_{ij}(x,\xi,\omega)\phi_i(\xi,\omega) d\Gamma_\xi + \int_\Omega T_{ij}(x,\xi,\omega) b_i(\xi,\omega) d\Omega_\xi + t_j^o(x,t) \end{aligned} \tag{3}$$

If the body is made by a fluid, the following functions represent the displacement field and pressures:

$$\begin{aligned} u_n^f(x,\omega) &= \frac{1}{2}\psi(x,\omega) + \frac{1}{\rho\omega^2}\int_\Gamma \frac{\partial G^f(x,\xi,\omega)}{\partial n}\psi(\xi,\omega) d\Gamma_\xi + \frac{1}{\rho\omega^2}\int_\Omega \frac{\partial G^f(x,\xi,\omega)}{\partial n} b^f(\xi,\omega) d\Omega_\xi \\ p^f(x,\omega) &= \int_\Gamma G^f(x,\xi,\omega)\psi(\xi,\omega) d\Gamma_\xi + \int_\Omega G^f(x,\xi,\omega) b^f(\xi,\omega) d\Omega_\xi \end{aligned} \tag{4}$$

where $\psi(x, \omega)$ is the force density in the fluid, ρ is the fluid density, $G^f(x, \xi, \omega)$ is the Green function for the fluid and is given by $G^f(x, \xi, \omega) = \frac{\rho\omega^2}{4i} H_0^{(2)}(\omega r/c^f)$, $H_0^{(2)}$ is the Hankel function of the second kind and zero order, r is the distance between x and ξ, c^f is the fluid velocity. The superscript f denotes fluid. Fig. 1 shows a schematic representation of an offshore structure under the incidence of seismic motions. H_a represents the water depth and γ is the incident angle of seismic waves.

The boundary conditions of the problem studied are:

(a) At the free surface of the water the pressure is zero, *i.e.*:

$$p^f = 0 \tag{5}$$

(b) In the seabed:

(b.1) Continuity of normal displacement

$$u_i(x,\omega) n_i = u_n^f(x,\omega) \tag{6}$$

(b.2) Shear stress is zero in solid–water interface:

$$(\delta_{ij} - n_i n_j) t_j(x,\omega) = 0 \tag{7}$$

(b.3) Stresses in the solid are balanced with water pressure:

$$t_i(x,\omega) n_i = -p^f(x,\omega) \tag{8}$$

where n_i is the unit normal vector associated with direction i, $u_n^f(x, \omega)$ is the displacement normal to the interface surface and $p^f(x, \omega)$ is the water pressure.

According to the boundary conditions, Eqs. (5)–(8) and taking into account equation (3) and (4), we can write:

$$\int_\Gamma G^f(x,\xi,\omega)\psi(\xi,\omega) d\Gamma_\xi = 0 \tag{9}$$

$$\begin{aligned} &\left[\int_\Gamma G_{ij}(x,\xi,\omega)\phi_j(\xi,\omega) d\Gamma_\xi + \int_\Gamma G_{ij}(x,\xi,\omega) b_j(\xi,\omega) d\Omega_\xi + u_i^0(x,\omega)\right] n_i \\ &= \frac{1}{2}\psi(x,\omega)\delta_{ij} + \frac{1}{\rho\omega^2}\left[\int_\Gamma \frac{\partial G^f(x,\xi,\omega)}{\partial n}\psi(\xi,\omega) d\Gamma_\xi\right] \\ &+ \int_\Omega \frac{\partial G^f(x,\xi,\omega)}{\partial n} b^f(\xi,\omega) d\Omega_\xi \end{aligned} \tag{10}$$

$$\begin{aligned} (\delta_{ij} - n_i n_j) &\left[\frac{1}{2}\phi_i(\xi,\omega)\delta_{ij} + \int_\Gamma T_{ij}(x,\xi,\omega)\phi_j(\xi,\omega) d\Gamma_\xi \right. \\ &\left. + \int_\Omega T_{ij}(x,\xi,\omega) b_j(\xi,\omega) d\Omega_\xi + t_i^0(x,\omega)\right] = 0 \end{aligned} \tag{11}$$