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# Seismic amplifications from offshore to shore

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## ABSTRACT

The objective of this study is to determine numerical estimations of seismic amplifications of waves traveling from offshore to shore considering the effect of sea floor configurations. According to the Boundary Element Method, boundary elements were used to irradiate waves and density force can be determined for each element. From this hypothesis, Huygens' Principle is implemented since diffracted waves are constructed at the boundary from which they are radiated and this is equivalent to Somigliana's theorem. Application of boundary conditions leads to determine a system of integral equations of Fredholm type of second kind, which is solved by the Gaussian method. Various numerical models were analyzed, a first one was used to validate the proposed formulation and some other models were used to show various ideal sea floor configurations to estimate seismic amplifications. Once the formulation was validated, basic slope configurations were studied for estimating spectra of seismic amplifications for various sea floor materials. In general terms, compressional waves (P-waves) can produce seismic amplifications of the incident wave in the order of 2–5. On the other hand, distortional waves (S-waves) can produce amplifications up to 5.5 times the incident wave. A relevant finding is that the highest seismic amplifications due to an offshore earthquake are always located near the shore-line and not offshore despite the seafloor configuration.

## 1. Introduction

The majority 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 compressional wave and are reported to cause damage to ships and their effect on floating structures is a matter of great concern (Takamura et al. [2]).

Trevorrow et al. [3] developed measurements of ambient seismic noise using ocean-bottom seismometers. They obtained the vertical components of seabed acceleration, in shallow waters, only, and then extrapolations of the measured pressures and seabed motions to deeper water conditions were made. Ocean-bottom seismometers were also used to quantify gravity-wave-coupled seabed motion, and to determine the propagation velocity and spectral characteristics of micro seismic noise [4]. Moreover, underwater sensor stations were used for continuous registration of bottom movements in the North Sea. The energy of the sea waves mainly induces the bottom motion and microseisms [5]. Other important contributions to data acquisition in seabed for seismic applications can be consulted in [6–9].

Marine structures are generally vulnerable to strong seismic motions. However, the attention given to the seismic response of marine structures under strong seismic wave has been limited [10]. Using the Finite Element Method (FEM), Jianhong [10] evaluated the seismic amplifications in breakwater structures and found that the amplification of the horizontal seismic response is stronger than the vertical seismic one. FEM was also employed to study the propagation of tsunamis generated by earthquakes and the impact of the water waves against the coast of a circular island was calculated [11]. Moreover, the seismic performance of the submarine pipeline and the water/pipeline interactions during the seismic events was studied by Zeinoddini et al. [12] and Yan and Cheng [13]. FEM has been also used to model submerged floating tunnels under seismic propagation [14].

On the other hand, Boundary Element Method (BEM) was applied to study the earthquake-induced hydrodynamic pressures on rigid axisymmetric offshore structures of arbitrary shape [15]. A boundary integral equation was derived assuming that the seabed is a semi-infinite homogeneous elastic solid in order to analyze the seaquake induced hydrodynamic pressure acting on the

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floating structure [2]. Pressure profile through water depth and seismic amplifications in irregular bathymetries using BEM were reported by Rodríguez-Castellanos et al. [16] and Martínez-Calzada et al. [17].

This paper applies the Boundary Element Method (BEM) to calculate the seismic amplifications 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. Several seabed configurations and materials are modeled to exemplify the seismic amplification. In the following paragraphs a brief explanation of the BEM applied to sea bottom subjected to seismic motions is given.

## 2. Formulation of the problem

This paper provides a numerical solution to estimate seismic amplifications of waves propagating from offshore to shore considering sea floor configuration effects. Fig. 1 shows various types of offshore structures for the oil industry, it can be observed that the type range vary from self-supported to floating, which is dictated by water depth. Seismic response of these structures is a function of the stiffness system that links the structure to the sea floor. Regarding sea floor configuration it can be modeled as various slope-plateau steps from offshore to shore. Considering this sea floor model, a two dimensional (2D) coordinate system is chosen to develop the formulation proposed in this paper.

To apply our integral formulation we need to define the boundary conditions and the regions in which the problem is divided, then Fig. 2 establishes.

Consider the movement of an elastic, homogeneous and isotropic solid of volume $\Omega^E$, delimited by the boundary $\Gamma^E(\partial_1 E \cup \partial_2 E)$. Introducing fictitious sources of density $\phi_i(\mathbf{x}, \omega)$ on $\Gamma^E$, the total fields of displacements $\left(u_j^E(\mathbf{x}, \omega)\right)$ and tractions $\left(t_j^E(\mathbf{x}, \omega)\right)$ can be written, in frequency domain, as Banerjee and Butterfield [18]:

$$\begin{aligned} u_j^E(\mathbf{x}, \omega) &= \int_{\Gamma^E} G_{ij}^E(\mathbf{x}, \boldsymbol{\xi}, \omega)\phi_i(\boldsymbol{\xi}, \omega)d\Gamma_\xi^E \\ &\quad + \int_{\Omega^E} G_{ij}^E(\mathbf{x}, \boldsymbol{\xi}, \omega)b_i(\boldsymbol{\xi}, \omega)d\Omega_\xi^E + u_j^{oE}(\mathbf{x}, \omega), \\ t_j^E(\mathbf{x}, \omega) &= c_1\phi_i(\mathbf{x}, \omega)\delta_{ij} + \int_{\Gamma^E} T_{ij}^E(x, \boldsymbol{\xi}, \omega)\phi_i(\boldsymbol{\xi}, \omega)d\Gamma_\xi^E \\ &\quad + \int_{\Omega^E} T_{ij}^E(\mathbf{x}, \boldsymbol{\xi}, \omega)b_i(\boldsymbol{\xi}, \omega)d\Omega_\xi^E + t_j^{oE}(\mathbf{x}, \omega) \end{aligned} \tag{1}$$

where $G_{ij}^E(\mathbf{x}, \xi)$ and $T_{ij}^E(\mathbf{x}, \boldsymbol{\xi})$ are the Green's functions for displacements and tractions, respectively, which can be found in [16]. The

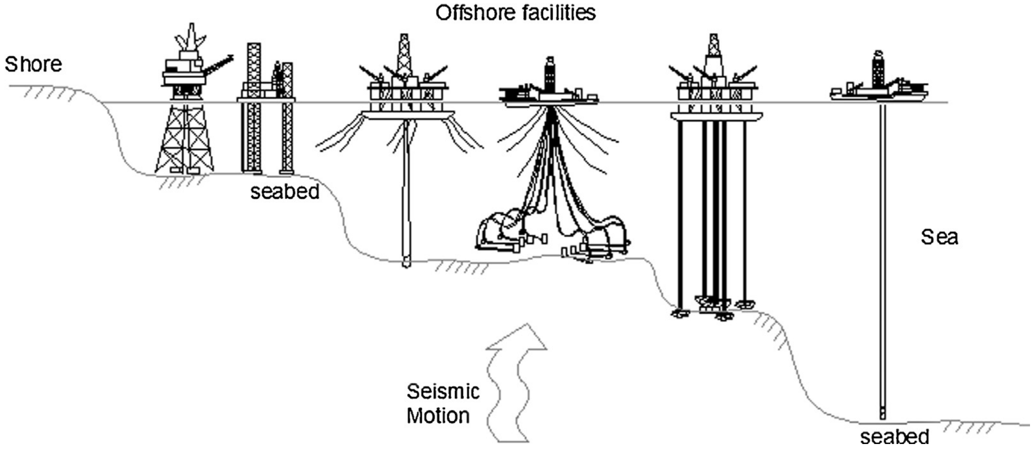

**Fig. 1.** Concept solutions for the offshore oil industry and slope-plateau sea floor model used for the seismic response study. A two dimensional problem is considered.

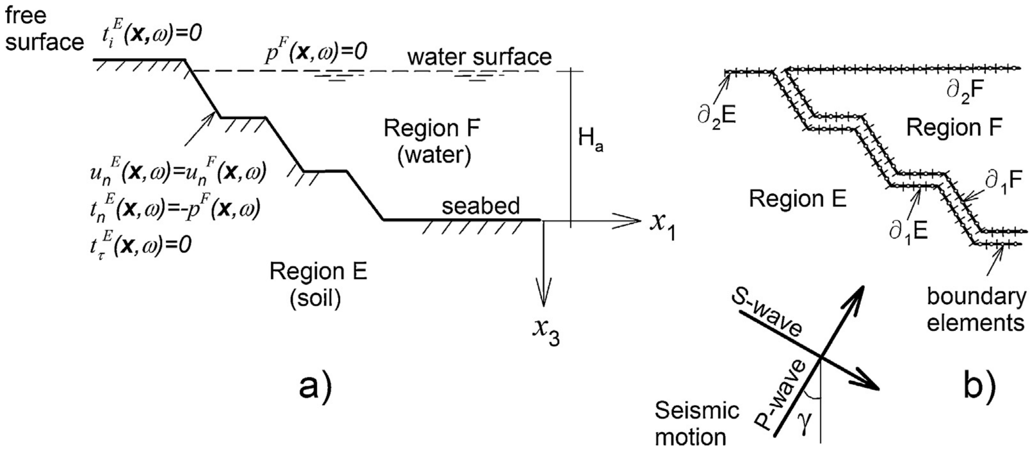

**Fig. 2.** (a) Boundary conditions; (b) boundary mesh.