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Theoretical analysis of extreme wave oscillation in Paradip Port using a 3-D boundary element method

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ABSTRACT

A mathematical model is developed to estimate the amplification of multidirectional random waves in the Paradip port, Odisha, India under the resonance conditions. A 3-D boundary element method with the consideration of variable bathymetry is utilized for solving Laplace equation in an irregular domain including the partial reflection boundary condition. The current numerical scheme is validated through the comparison of simulation results with previous well-defined studies along with measurement data for the rectangular harbor. Six key recorder stations are chosen as port location of moored ship to analyze the wave response in the Paradip port for multidirectional random waves. Further, wave spectrum is also estimated based on Fast Fourier Transformation (FFT) with respect to wave period at six recorder stations. Actual bathymetry of Paradip port is utilized to estimate the wave height ratio at each record station for the incident waves with different directions. Further, the resonance frequencies are determined for each directional incident wave and safe locations in Paradip port is also identified based on the simulation results. Thus, the proposed numerical scheme can be utilized to foster the prediction of wave profile in the realistic ports or harbors with complex geometries for the safe navigation.

1. Introduction

Extreme wave height in coastal regions has a significant impact on ports or harbors connecting to open sea. In recent decades, Paradip port has experienced extreme wave height approximately 3–4 m due to the strong winds generated by cyclone and typhoon in the Bay of Bengal. High amplitude incident waves with resonant frequencies can damage the coastal structures, moored ships, and ropes in Paradip port. However, it is designed to protect the coastal structures and moored cargo ships etc. from the high amplitude long waves. It is required to construct an efficient numerical model to analyze the resonance phenomenon in Paradip port with actual bathymetry. Paradip port is one of a major industrial port located in Jagatsinghpur district, Odisha, India on the southeast coastal boundary of India in the Bay of Bengal.

Long period waves frequency matches the natural resonant frequency of harbors or ports, it generates high amplification in the inner region of harbor on the free water surface (Miles and Munk, 1961). In 1963, Ippen and Goda analyzed the wave induced amplification factor in a rectangular harbor. Moreover, Hwang and Tuck (1970) and Lee (1971) utilized the Helmholtz equation for the analysis of wave induced oscillation in an arbitrarily shaped harbor by using the boundary element method (Chou and Han, 1994, 1993; Hoernig, 2010). Researchers have used the Boundary Element Method (BEM) to estimate the amplification factor under the resonance conditions in irregular shaped harbor including partial reflection boundaries (Bellotti, 2007; Cerrato et al., 2016; Chen et al., 2015; Kumar et al., 2014, 2013; Lee, 2004; Lee and Williams, 2002).

There is a variety of external forcing for inducing the significant wave oscillations such as tsunami waves, longshore propagating waves, strong typhoons and low-high pressure fluctuations near harbor (Bellotti et al., 2012; De Jong and Battjes, 2004; Dong et al., 2010). Several researchers have worked on tsunami waves, the most destructive incident waves are generated by a strong earthquake (Monserrat et al., 2006; Rabinovich, 1997) e.g. Sumatra tsunami (Rabinovich et al., 2006; Rabinovich and Thomson, 2007). Traditionally, the Mild Slope Equation (MSE) or modified MSE is solved by various numerical methods as Finite Difference Method (FDM), Finite Element Method (FEM) and Spectral Element Method (SEM) to analyze the combined wave refraction-diffraction and partial reflection (Berkhoff, 1976, 1972; Cerrato et al., 2017; Hsiao and Fang, 2005; Lee et al., 2006; Li and Anastasiou, 1992; Liu et al., 2008; Sharma et al., 2014). Nevertheless, numerical schemes based on FDM and FEM have some deficiency such as open and partial reflection boundary conditions are difficult to address. Further, these deficiencies have been studied by

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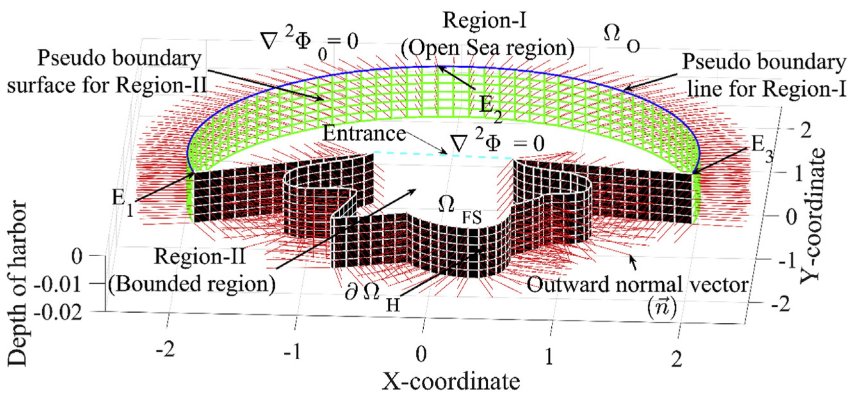

Fig. 1. The geometry of 3-D boundary element model for the arbitrarily shaped harbor is given. The black block represents the solid harbor walls, blue line denotes the Pseudo boundary and red arrows represent the outward normal vectors. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

several researchers such as Chen (1986) and Tsay et al. (1989) utilizing hybrid FEM formulation including the bottom friction (Mei et al., 2005).

In 3-D boundary element model, the bottom topography (variable bathymetry) is considered while in 2-D boundary element models depth is assumed as constant. Since the topography and bathymetry of the harbor play a crucial role to analyze the resonance behaviour inside the port. Yalciner and Pelinovsky, 2007 estimated the oscillation in the Sea of Marmara with irregular geometry and bathymetry. Further, Rabinovich (1997) analyzed the effect of the bottom topography on the tsunami waves (Slinn et al., 2000). Three-dimensional (3-D) boundary element modeling gives better accuracy to analyze the wave induced oscillations in an irregular bounded domain. Recently Kumar et al. (2014, 2013) implemented the boundary element method on realistic Pohang New Harbor, South Korea, Bellotti and Franco, 2011 and Guerrini et al., 2014 have work in Marina di Carrara harbor in Italy. Further, the redesigning or modification of the original port or harbor, simulation result is conducted for the safety of moored ship motion (Kumar et al., 2016; Kwak et al., 2012). These studies have helped to reduce the wave-induced oscillation in realistic harbors and ports. The major drawback for the 3-D Boundary element model is that it required the more computation time as compared to the 2D boundary element model due to the increment of mess element consideration of bottom topography.

In the context of this paper, we present an efficient 3-D boundary element formulation for a complex geometry domain with variable bathymetry to analyze impacts of the multidirectional random waves under the resonance conditions. The partial reflection boundary condition (Chou and Han, 1993) is also utilized along with kinematic and dynamic free surface boundary conditions for shallow water waves. The Green's theorem is applied to solve the Laplace equation in the interior or bounded domain where the depth variation is arbitrary distributed and Helmholtz equation in exterior or unbounded domain with constant depth. The interior domain of a port is bounded by four connected boundaries to each other, i.e., port walls, free surface, pseudo boundary and bottom topography. Finally, the numerical approximation is obtained after matching the solution at the pseudo boundary surface, the common boundary in interior and exterior domain. The current numerical approach is applied on a realistic port in India, i.e., the Paradip port, the second largest port of India. To validate the numerical scheme, comparison is shown with rectangular and Long beach harbor, California. Further, numerical scheme for wave spectrum is validate with the given in-situ measurement data for Pohang New Harbor, South Korea. The numerical convergence is obtained to verify the present numerical scheme for the Paradip port. Wave spectrum for multi-directional random wave is analyzed for a realistic harbor with partially reflecting condition by using the Mitsuyasu's spectrum. Amplification factor is evaluated inside the Paradip port to locate the safe locations for moored ship.

This paper is organized as follows: In section 2, the boundary element formulation for the variable bathymetry and analytical approximation for constant depth are estimated under the resonance conditions. The comparison and convergence analysis for the current numerical scheme is covered in section 3. The proposed 3-D boundary element model is implemented on realistic Paradip port, Odisha, India for multi-directional random waves in section 4. Finally, section 5 gives brief summary and conclusion remarks.

2. Mathematical formulation

In Fig. 1, the pseudo boundary $E_1E_2E_3$ is divided the fluid region into two regions: Region-I, i.e., the open sea region (exterior) Ω_O with constant water depth and Region-II, i.e., the bounded region (interior) enclosed by free surface Ω_{FS}, bottom topography or variable bottom Ω_{SB}, break waters including harbor walls Ω_H and pseudo boundary ($E_1E_2E_3$). The Cartesian coordinate system is taken with $z-$ axis vertically upward and $x-$ axis along shoreline and $y-$ axis towards the open sea. The main reason to consider circular boundary instead of simple line at the port entrance because at the entrance and exterior boundary, the incident waves are diffracted, partially reflected and scatter from the interior harbor boundary. The matching boundary condition at the entrance cannot capture the partial reflection, diffraction and refraction of the incident wave on the exterior harbor boundaries. However, the matching boundary condition at some distance away from entrance (at circular pseudo boundary) can estimate the scatter waves including diffraction, refraction and partial reflection at the entrance, exterior and interior harbor boundary. The outward normal vector is taken on the solid boundary walls and pseudo boundary (see Fig. 1).

For simplicity, we assumed that the fluid flow is irrotational, fluid is inviscid and incompressible. Velocity vector $\vec{V}$ can be defined as the gradient of potential function $\Phi(x, y, z; t)$. Thus, the continuity equation is given as follows:

$$\nabla\cdot\vec{V} = \nabla^2\Phi = 0. \tag{2.1}$$

The linear incident waves come from the open sea region with angular frequency $\omega = 2\pi/T$, T is incident wave period and A_i is the amplitude of the incident wave. Thus, the fluid motion for both the regions will have the velocity potentials function Φ of the form

$$\Phi(x, y, z; t) = -\frac{igA_i}{\omega}\phi(x, y, z)e^{-i\omega t}, \tag{2.2}$$

where i is the imaginary number $i = \sqrt{-1}$ and g is the gravitational acceleration, also potential function $\phi(x, y, z)$ satisfies the Laplace equation

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0. \tag{2.3}$$