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Study of non-linear wave motions and wave forces on ship sections against vertical quay in a harbor

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Abstract

The resonance phenomenon of fluid motions in the gap between ship section, seabed and vertical quay wall is studied numerically and experimentally. The natural frequency of the fluid motions in the gap is derived. A two-dimensional time-domain coupled numerical model is developed to calculate the non-linear wave forces acting on a ship section against vertical quay in a harbor. The fluid domain is divided into an inner domain and an outer domain. The outer domain is the area between the left side of ship section and the incident boundary, where flow is expressed by Boussinesq equations. The rest area is the inner domain, which is the domain beneath the ship section plus the domain between the right side of ship section and vertical quay wall. The flow in the inner domain is expressed by Newton's Second Law. Matching conditions on the interface between the inner domain and the outer domain are the continuation of volume flux and the equality of pressures. The numerical results are validated by experimental data.

Keywords: Resonance; Natural frequency; Coupled model; Boussinesq equations; Newton's Second Law

1. Introduction

The motions of moored ship in a harbor are the critical problem of harbor design. The bump of moored ship against quay is important for the structural strength and stability. Resonant fluid motions in the gap between moored ship, seabed and quay wall can be generated while the incident wave frequency approximates to the natural frequency of fluid motions in the gap. Large wave forces on moored ship will be induced by the resonant fluid motions and how to analyze the resonant motions is important for the motions of the moored ship and bump forces. Zou and Bowers (1993) presented a way to solve the movement of moored ship in the harbor: first obtaining wave conditions in the harbor and the wave force action on the ship, then studying the dynamic response of the mooring ship system under the action of the wave. For the first question, Qi et al. (2003) developed a coupled model for numerical simulations of non-linear wave forces on ship against vertical quay, which is based on the combination of Boussinesq equations with the Reynolds averaged Navier–Stokes. Just as the models in which Laplace (Boo et al., 1994; Wu and Taylor, 1994; Celebi et al., 1998; Turnbull et al., 2003) or N–S equation (Hirt et al., 1975; Nichols and Hirt, 1981; Park and Kim, 1998) are resolved by boundary element method (BEM), finite-element method (FEM) or finite difference method (FDM), it is also difficult for the coupled model to analyze the resonance phenomenon of waves between ship and vertical quay wall since the distance between them is too small to be resolved by the FDM.

In this paper, the resonance phenomenon of fluid motions in the gap between ship section, seabed and vertical quay wall is studied by experiment and numerical simulation. The natural frequency of the fluid motions in the gap is derived. An efficient and simple algorithm for simulating non-linear wave forces on ship section against vertical quay wall in a harbor is developed, which is based

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on the combination of Boussinesq equations with Newton's Second Law. The numerical results are validated by experimental data.

In Section 2, the coupled model is illustrated in detail. The physical experiments are described in Section 3. In Section 4, the natural frequency of the fluid motions in the gap between ship section, seabed and vertical quay wall is derived. The comparisons between numerical results and experimental data are reported in Section 5 and the resonance phenomenon of fluid motions in the gap is analyzed in Section 6. The conclusions are given in Section 7.

2. Coupled model

2.1. Division of computation domain

As shown in Fig. 1, we use a Cartesian coordinate system $O{-}XY$ with the origin on the still water surface and the Y pointing upwards. The fluid domain is divided into the inner domain Ω_2 and the outer domain Ω_1. The outer domain Ω_1 is the area between the left side of the ship section and the incident boundary, where the flow is governed by Boussinesq equations. The rest area is the inner domain Ω_2, which is the domain beneath the ship section plus the domain between the right side of ship section and vertical quay wall. The flow in the inner domain is governed by Newton's Second Law. Matching conditions on the interface $\overline{a_1a_2}$ between the inner domain and the outer domain are the continuation of volume flux and the equality of pressures. In Fig. 1, a_1 and a_2 are the ends of the interface $\overline{a_1a_2}$, h is the still-water depth, d is the draft of ship section, δ_1 is the gap width between ship bottom and seabed, δ_2 is the gap width between ship section and vertical quay wall, p_1 is the pressure at the interface $\overline{a_1a_2}$, p_2 is the pressure at the interface $\overline{b_1b_2}$ that separates the fluid between the ship bottom and seabed from the fluid between the right side of ship section and vertical quay wall, b_1 and b_2 are the ends of the interface $\overline{b_1b_2}$, β is the angle between $\overline{b_1b_2}$ and vertical quay wall, B is the width of ship section, u_1 is the horizontal velocity in the gap between ship bottom and seabed, u_2 is the vertical velocity in the gap between ship section and vertical quay wall, ς is the wave elevation in the gap between ship section and vertical quay wall.

2.2. Governing equations in the outer domain Ω_1

The governing equations in the outer domain Ω_1 are the one-dimensional form of the higher-order Boussinesq equations derived by Zou (2001), which reads

$$\zeta_t + [(h+\zeta)\bar{u}]_x = 0, \tag{1}$$

$$\bar{u}_t + \bar{u}\bar{u}_x + g\zeta_x + G = R, \tag{2a}$$

$$\begin{aligned} G = & -\left\{HD\left[\tfrac{1}{3}(H\bar{u}_x)_x + \tfrac{1}{3}(h_x\bar{u})_x\right] + \tfrac{1}{6}h_x D(H\bar{u}_x)\right. \\ & \left. + \zeta_x D\left[\tfrac{2}{3}H\bar{u}_x + h_x\bar{u}\right]\right\}, \end{aligned} \tag{2b}$$

$$\begin{aligned} R = & \frac{1}{6}h^2 M_{xx} - \frac{1}{8}h^3\left(\frac{M}{h}\right)_{xx} + \frac{1}{40}h^4\left(\frac{M}{h^2}\right)_{xx} \\ & + \frac{1}{48}h^3\left[(h_x\bar{u}_t)_x + h_x\bar{u}_{xt}\right]_{xx} \\ & - \frac{1}{80}h^4\left\{\frac{1}{h}\left[(h_x\bar{u}_t)_x + h_x\bar{u}_{xt}\right]\right\}_{xx}, \end{aligned} \tag{2c}$$

where $M = \bar{u}_t + \bar{u}\bar{u}_x + g\zeta_x$, $D = (\partial/\partial t) + \bar{u}(\partial/\partial x)$, $H = h + \zeta$, ζ is the wave elevation, $\bar{u}$ is the depth-averaged horizontal velocity, g is the gravitational acceleration and t is the time.

Space-staggered grids are used with depth-averaged velocity $\bar{u}$ defined at the time level h and wave elevation ζ at time level $n - \frac{1}{2}$. The resulting equations of Eqs. (1) and (2) are discretized in Predictor–Corrector scheme by a FDM.

2.3. Governing equations in inner domain Ω_2

As shown in Fig. 1, the profile of ship section is taken as rectangle. The gap δ_1 and the gap δ_2 are constant and small compared to water depth, so the velocity u_1 and u_2 are uniform in the gaps. The motions of the fluid in the gaps will satisfy Newton's Second Law

$$F = ma, \tag{3}$$

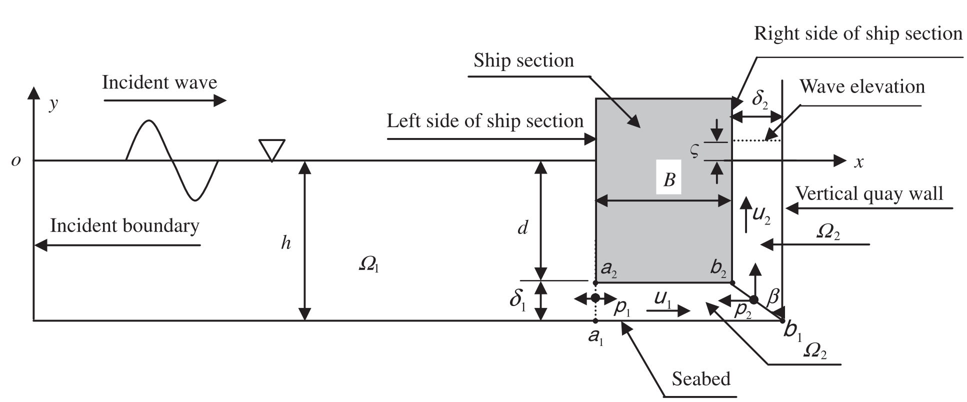

Fig. 1. Coupled model.