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Boundary element study of wave impact on a vertical wall with air entrapment

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ABSTRACT

Effect of the air entrapped between an overturning wave and a vertical wall plays an essential role in the physical process of wave impact. However, due to complexity of both the physical phenomena and numerical techniques, conventional simulations with boundary element method (BEM) can only deal with the wave overturning stage, and calculations have to be terminated before the wave front impacts on the wall. This study aims to achieve the complete process simulation of wave impact with air entrapment using BEM. The key idea is to introduce a multi-scale algorithm with the help of a stretched coordinate system for the local impact zone. Interesting phenomena are observed indicating effects of the entrapped air on wave impact dynamics. In particular, free inner jets are found to form periodically inside the entrapped air cavity. The free jet has the trend to lead to the division of the cavity, indicating an initial bubble generation during wave impact. Effects of the air pressure on the impact process with air entrapment are also studied, where an analytical deduction based on the conservation law of conservation is used to explain the findings.

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1. Introduction

Vertical sea front is commonly used in coastal structures such as breakwaters, ports and seawalls. In rough sea conditions, the vertical wall is continuously impacted by shoaling waves. A severe wave impact can induce very high pressures in a short duration, and cause a catastrophic damage or failure to the structure. Thus, a systematic understanding of the wave impact mechanism is of great importance for engineering designs of these coastal structures.

A number of laboratory and field experiments have been conducted on wave impact problems since Bagnold [1], among which effects of the air entrapped between an overturning wave and a vertical wall have been highlighted. Chan and Melville [2] showed that the air entrapped played an essential role in the physical process of impact pressure. Oumeraci et al. [3] pointed out that the entrapped air could transfer to isolated bubbles after the compression and explosion processes, which contributed to the breaking of wave. Hattori et al. [4] found that when a small amount of air was entrapped, a considerable increase of the impact pressure occurred. In Hull and Müller [5], the maximum impact pressure was found to be created by a plunging waver with a large entrapped air pocket on the wall. Through large-scale experiments, Bullock et al. [6] compared distinctive features of low-aeration and high-aeration impacts and found that high levels of aeration can increase both the force and impulse on the structure. Bredmose et al. [7] studied the low-aeration impacts, and found that the air-pocket in an overturning wave can transform to a turbulent air–water mixture after wave break, which tended to distribute the impact pressure more widely over the wall. Hu et al. [8] further confirmed in experiments that the highest force on the wall occurred under the large air pocket wave impact.

These physical experiments have greatly promoted people's understanding on the process of wave impact with air entrapment. However, most experimental studies are limited due to the fact that the experiment is normally based on a specific experimental set-up with a fixed scale. To better understand the complex mechanism involved and to save time and cost, many other researchers have investigated the wave impact problem using numerical approaches.

Pioneered by Cooker and Peregrine [9], the boundary element method (BEM) based on the fully nonlinear potential-flow theory has been widely used aiming at the wave plunging simulations before any impact happens (e.g. Dommermuth et al. [10]; Grilli et al. [11]; Greco et al. [12]). However, as the wave impact usually starts from a single contact point before an extremely fast change of the free surface velocity happens, boundary elements within a tiny impact zone and time steps around the impact instant have to be extremely small. This poses a major technical challenge for the boundary element simulations. Restricted to this fact, most BEM simulations only consider the wave

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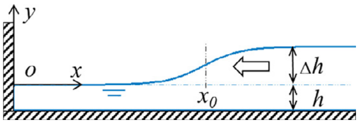

Fig. 1. The initial wave model.

overturning stage, and calculations have to be terminated when the wave front impacts on the wall. In this situation, effects of the air entrapment are normally out of consideration. In order to continue the calculation, Tanizawa and Yue [13] let the wave flow pass the wall around the impact instant, which is not physically true. Zhang et al. [14] simplified the wave tip impact instant as a liquid wedge perpendicularly striking on the wall with a constant speed, so that similarity solution could be used for the local flow within a short duration. This method provides a rational approximation to the initial direct impact stage, although the following limitations still exist, that: (i) it is very difficult to maintain a smooth transition of velocities and free surface profiles between the assumed wedged-shape wave front and the remaining flow; (ii) the liquid wedge approximation may work well mainly for slender plunging wave crest with large curvature in the front. Although similarity solution aiming at impact by a liquid wedge was also investigated later in references such as Duan et al. [15], more efforts on overcoming the technical difficulty of BEM in wave impact simulation were not further reported.

At present, a majority of numerical studies have tended to apply a multiphase Computational Fluid Dynamics (CFD) method which skips the above-mentioned difficulty. For example, Gao et al. [16] and Hu et al. [8] used OpenFOAM to solve wave impact on a wall as a multiphase flow problem. Both references used the Volume of Fluid (VOF) interface capturing approach. Some other examples include Guilcher et al. [17] and Altomare et al. [18], who used the smoothed particle hydrodynamics (SPH) method to model the wave impact process. However, unlike the BEM which tracks the free surface in a 'sharp' manner, the free surface is blurred using either VOF or particle methods. An extremely small time step and large number of elements or particles have to be used, in order to capture the fast change of wave velocity and pressure. In other words, these typical multi-phase CFD methods are normally uneconomic for the present wave impact problem.

From the literature review, it can be found that very limited studies have achieved a whole-process BEM simulation of the wave impact problem, due to the above-mentioned technical difficulty. This study aims to resolve this technical difficulty by introducing a multi-scale algorithm with the help of a stretched coordinate system. The brief idea of this technique is introduced as follows. When an overturning wave strikes the wall, a small subdomain near the impact zone is solved by BEM in a stretched coordinate system, for a microscopic capture of local flow details. The far field condition is matched with that from the outer fluid domain, where the wave is assumed to keep propagating without the wall. As the impact zone develops to a certain scale, these two subdomains are combined into one for the subsequent BEM simulations. The pressure variation of the trapped air can be taken into account without any difficulty. Based on this novel technical approach, wave impact on a vertical sea wall commonly seen in the domain of coastal engineering will be investigated. In particular, effects of the entrapped air and its initial pressure on the wave impact dynamics will be analyzed in detail.

2. Mathematical model and numerical procedure

2.1. The initial wave model

The model of a shoaling wave propagating towards a vertical wall over a flat horizontal bed is used to generate wave impact. To do this, the initial wave is given a gradual, monotonic increase in surface elevation as in Fig. 1. When it propagates, the wave can steepen and develop into a plunging wave, which has been described in Cooker and Peregrine [9].

A 2D Cartesian system o–xy is defined with the x axis pointing right on the still free surface and the y axis vertically pointing upwards on the wall. In the following sections, the still water depth h, gravity acceleration g and water density ρ are used as basis for nondimensionalization. To be specific, the non-dimensional length, velocity u, time t, and pressure P are obtained by dividing corresponding variables with h, $\sqrt{gh}$, $\sqrt{h/g}$ and ρgh, respectively.

To generate a shoaling water wave, the horizontal velocity of the flow averaged along the vertical direction is chosen to take the form (Cooker and Peregrine [9])

$$\bar{u}(x) = -\frac{1}{2}u_0\left\{1+\tanh\left[k(x-x_0)\right]\right\} \tag{1}$$

which corresponds to a uniform flow with velocity $-u_0$ at $x\rightarrow\infty$ and zero at $x\rightarrow-\infty$. The parameter k in Eq. (2) is used to control the steepness of the wave front. The resulting free surface profile from Airy's theory (e.g. Mei [19]) for shallow water waves then takes the form

$$f(x) = -\bar{u}(x) + \frac{1}{4}\bar{u}(x)^2 \tag{2}$$

which rises gradually from 0 at $x\rightarrow-\infty$ to $\Delta h = u_0 + u_0^2/4$ at $x\rightarrow\infty$. When a rigid wall is placed at $x=0$, the initial water depth there is approximately equal to 1 after nondimensionlization if x_0 in Eq. (1) is sufficiently large.

2.2. The boundary value problem

Potential-flow theory that assumes the fluid to be inviscid, incompressible, and flow-irrotational is used to simulate the wave impact process. The velocity potential φ whose gradient is the fluid velocity is introduced to describe the flow. Laplace's equation is satisfied in the fluid domain

$$\nabla^2\phi(x,y,t) = 0 \tag{3}$$

Impermeable conditions are satisfied on the vertical wall and horizontal seabed as

$$\frac{\partial\phi}{\partial n} = 0 \tag{4}$$

An open boundary is imposed on the right side of the fluid domain with a sufficient distance away from the wall. In this study, its position is determined by $x_\infty = x_0 + C/k$, where C satisfies $|1-\bar{u}(C)/u_0| < 10^{-4}$. The uniform flow condition at $x\rightarrow\infty$ from Eq. (1) is applied on the open boundary as

$$\frac{\partial\phi}{\partial n} = -u_0 \tag{5}$$

The Lagrangian-type kinematic and dynamic boundary conditions are applied on the instantaneous free surface as

$$\frac{d\vec{r}}{dt} = \nabla\phi \tag{6}$$

$$\frac{d\phi}{dt} = \frac{1}{2}\nabla\phi\cdot\nabla\phi + \frac{1}{2}u_0^2 + (\Delta h - y) - (P - P_0) \tag{7}$$

where $\vec{r} = (x,y)$ denotes the position of an arbitrary point on the free surface, and P_0 is the non-dimensional atmospheric pressure. On the free surface connecting to the atmosphere, we have $P = P_0$. The trapped air is considered ideal, non-condensable and adiabatic, so that pressure in the cavity is governed by $P = P_0(\frac{V_0}{V})^\gamma$, where V is the cavity volume with V_0 its initial value, and $\gamma = 1.4$ is the heat ratio of air (see Oertel [20]).

For the initial incident wave described in Section 2.1, the corresponding velocity potential averaged over the depth is (e.g. Mei [19])

$$\bar{\phi}(x) = \int_{x_0}^{x}\bar{u}(x)dx = -\frac{1}{2}u_0\left\{x - x_0 + \frac{\ln\left[\cosh k(x-x_0)\right]}{k}\right\} \tag{8}$$

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