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Internal inlet for wave generation and absorption treatment

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ABSTRACT

A new method of implementing, in two-dimensional (2-D) Navier–Stokes equations, a numerical internal wave generation in the finite volume formulation is developed. To our knowledge, the originality of this model is on the specification of an internal inlet velocity defined as a source line for the generation of linear and non-linear waves. The use of a single cell to represent the source line and its transformation to an internal boundary condition proved to be an interesting alternative to the common procedure of adding a mass source term to the continuity equation within a multi-cell rectangular region. Given the reduction of the source domain to a one-dimensional region, this simple new type of source introduced less perturbation than the 2-D source type. This model was successfully implemented in the PHOENICS code (Parabolic Hyperbolic Or Elliptic Numerical Integration Code Series). In addition, the volume of fluid (VOF) fraction was used to describe the free surface displacements. A friction force term was added to the momentum transport equation in the vertical direction, in order to enhance wave damping, within relatively limited number of cells representing the sponge layers at the open boundaries. For monochromatic wave, propagating on constant water depth, numerical and analytical results showed good agreements for free surface profiles and vertical distribution of velocity components. For solitary wave simulation, the wave shape and velocity were preserved; while, small discrepancy in the tailing edge of the free surface profiles was observed. The suitability of this new numerical wave generation model for a two source lines extension was investigated and proven to be innovative. The comparisons between numerical, analytical and experimental results showed that the height of the merging waves was correctly reproduced and that the reflected waves do not interact with the source lines.

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1. Introduction

In laboratory flumes, a controlled paddle motion generates water waves to study their impacts on coastal structures, beach profiles, and other related coastal phenomena. Nowadays, an alternative to physical modeling, at laboratory scale, is the use of numerical wave tanks. With such tanks, based on numerical models, the variation of wave conditions and the modification of coastal structures are much easier to implement than with physical models.

For inviscid fluid, the Laplace equation associated with nonlinear free surface boundary conditions is usually solved numerically, using the boundary element method (Grilli et al., 2001). For most of coastal engineering applications, the Boussinesq equations are used when vertical variation is negligible. This model assumes that wave amplitude is small enough to ignore the wave dissipation effects by wave breaking (Wei et al., 1999).

To account for energy dissipation during water wave propagation, the Navier–Stokes equations are adopted. Models, based on these equations, for internal wave generation have been widely used to simulate 2-D wave propagation (Lin and Liu, 1999). Internal wave generation models may be subdivided in source line and source function types and present the advantage of avoiding the interference with the boundary conditions.

The source line method generates waves at a single point in the wave propagation direction. Waves are generated by adding, at each time step, an incremental water surface elevation computed by the resolution of the model equations. Larsen and Dancy (1983) were the first to use the source line method with the Boussinesq equations and suggested that the phase velocity is appropriate to account for the incremental water surface.

Brorsen and Larsen (1987) were the pioneers in using additional mass source term, for linear and non-linear wave generation, with the Laplace equation. The source function method requires several grids to overcome the discontinuity of the source at the wave generation band. It is based on the addition of a source term to the governing equations, either in the form of a mass source in the continuity equation or as a pressure forcing term in the Boussinesq equations (Wei et al., 1999). Based on internal mass source added to the Navier–Stokes equations, Kawasaki (1999) showed that the non-linear wave generator is appropriate to study wave breaking over submerged breakwater.

The waves may be generated using a wave-maker, modeled as a moving object within the water body. Its displacement is computed

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according to the wave-maker theory (Dong and Huang, 2001). Another elementary generation method is based on defining at the lateral boundary the free surface elevation and the velocity components corresponding to the desired generated wave (Lin and Liu, 1998).

To avoid the propagation of the wave toward open boundaries, and therefore their reflection, the common methods adopted are based on the addition of a sponge layer near the radiation boundary. The disadvantage of such damping zones is the increase of the number of computational cells required to cover the zone added to the active domain specially, in three dimensions (3-D) models. Another type of dissipation zone consists of an additional pressure applied to the free surface, which will dampen the vertical wave motion.

This study will focus on the implementation of an internal source line for linear and nonlinear wave generation in 2-D model based on Navier–Stokes equations. This model was integrated in the PHOENICS code. The numerical results are compared to the analytical solutions describing the symmetric and asymmetric behaviors of linear and nonlinear waves. For the merging of two solitary waves, the computed free surface profiles are compared to experimental results and analytical solutions.

2. Governing equations and boundary conditions

2.1. Internal wave generation

To generate numerically a given wave, based on the 2-D Navier–Stokes equations, Lin and Liu (1999) added a mass source term to the continuity equation in the source region Ω located within the computation domain (Fig. 1a). In this method, the source region has a rectangular shape defined by the length L_s (in the horizontal direction) and the height H_s (in the vertical direction). They summarized the applied rules for the optimal design of the source region. In this source region, a group of cells was adopted and the spatial variation of the source function was not considered. For incompressible fluid and unsteady flow, the mass conservation equation is modified as (Lin and Liu, 1999):

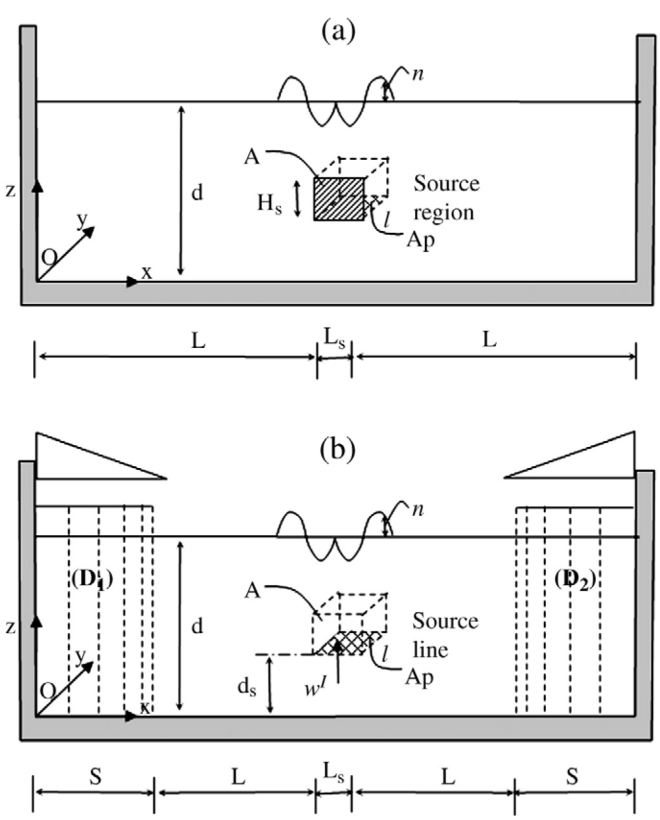

Fig. 1. Internal source for wave generation. a) The source region method proposed by Lin and Liu (1999); b) the developed horizontal source line method and computational domain for monochromatic wave generation.

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = s(t) \tag{1}$$

Where, u and w are the velocity components respectively in the x and z directions; $s(t)$ is an added mass source term depending on the type of generated wave.

It is noted that the desired value of $s(t)$ is imposed only in the source region Ω located within the computation domain; Otherwise $s(t) = 0$. If the dimension of the source region Ω is very small, we can neglect the spatial variation of the source function. The corresponding mass source term is given by:

$$s(t) = \frac{2C\eta(x_s, t)}{A} \tag{2}$$

The factor “2” in the preceding equation indicates that the wave energy is transported in both directions from the wave generation source region; C is the wave celerity; $\eta(x_s,t)$ is the free surface elevation at time t and at the source region location ($x = x_s$) and $A = L_sH_s$ is the area of the rectangular source region.

2.2. The internal inlet velocity

Based on the wave generation by mass source term developed by Lin and Liu (1999), we present a new method for wave generation by the specification of the inlet velocity on horizontal source line within the computational domain. In this method, small perturbation of flow field is expected given the relatively small source region height H_s compared to the total water depth d ($H_s << d$). In vertical line source, these parameters are of the same order of magnitudes ($H_s \approx d$), and velocity is specified on the left and right sides of source line. Since, the length of the source is much smaller than the wave length ($L_s << \lambda$), and the mass source term is independent of the space coordinates, only one cell is required for the definition of the suggested new horizontal source line.

The mass source tem $s(t)$ was transformed to an internal inlet $w^I(t)$ for its implementation into the PHOENICS code. The desired inlet velocity was computed based on the corresponding mass flux per unit time. In the finite volume scheme, used by the PHOENICS code, the mass source term is integrated over a control volume to give (Fig. 1):

$$q_v(t) = \iiint_{CV} s(t)dV = s(t)V = 2\frac{V}{A}C\eta\,(x_s, t) \tag{3}$$

The term q_v in the integrated mass source term represents the pulsating discharge for the generated wave; V is the volume of one cell (m^3); it is noted that in 2-D model (for example in x–z plane), the width l in y direction is such that: $l = 1$ m.

The ratio of the volume of the control cell to the source region area is given by:

$$\frac{V}{A} = \frac{A_pH_s}{A} = \frac{A_p}{L_s} \tag{4}$$

With, A_p is the source line section.

Thus, the discharge q_v can be expressed as:

$$q_v(t) = \frac{2C\eta(x_s, t)}{L_s}A_p \tag{5}$$

Following to Brorsen and Larsen (1987), the wave is generated on vertical source line and hence the distribution of horizontal fluid

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