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The Application of FBNWT in Wave Overtopping Analysis

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ABSTRACT: *A 2-D Fluent-based numerical wave tank (FBNWT) capable of simulating wave propagating and overtopping is presented. The FBNWT model is based on the Reynolds averaged Naiver - Stokes equations and VOF free surface tracking method. The piston wave maker system is realized by dynamic mesh technology (DMT) and user defined function (UDF). The non-iteration time advancement (NITA) PISO algorithm is employed for the velocity and pressure coupling. The FBNWT numerical solutions of linear wave propagation have been validated by analytical solutions. Several overtopping problems are simulated and the prediction results show good agreements with the experimental data, which demonstrates that the present model can be utilized in the corresponding analysis.*

1. Introduction

The reliable prediction of wave overtopping is important in the design and maintenance of coastal structures, such as breakwaters and sea dikes. Wave overtopping is a complex phenomenon, which involves wave shoaling, wave breaking, wave reflection, and turbulence effects on water spray. On the other hand, wave energy conversion devices of the overtopping type are needed to increase the overtopping discharge for maximum wave power absorption. Experimental research is restricted by the cost and scale effects. Therefore, it is necessary to establish a model for simulating the wave overtopping to analyze the corresponding problems.

Several experimental and numerical studies have been carried out to investigate the wave overtopping phenomenon. Saville (1995) performed small scale experimental tests for wave overtopping at sloping sea walls. Some studies have been undertaken to establish the relationship between the overtopping discharge and the characteristics of seawalls and waves, using the laboratory test data of Goda (1985), Besley et al. (1998), and Shankar et al. (2003). Jens et al. (2006) presented prototype testing of an overtopping wave energy converter. Kabayashi and Wurijanto (1989) utilized long wave equations to describe wave motion on onshore coastal structures. Non-linear shallow water equations were employed by Hu et al. (2000) to simulate the wave overtopping of coastal structures.

n the present paper, a 2-D fluent-based numerical wave ltank (FBNWT) based on the Reynolds averaged Naiver - Stokes (RANS) equations, standard $k-\varepsilon$ turbulence model, and VOF free surface tracking method, is applied to wave propagation along the wave flume, which will be validated by analytical solutions. Several benchmark problems will be calculated by the current numerical wave model. The reasonably good agreements with the experimental data shows that the 2-D FBNWT can be used to analyze wave overtopping and corresponding problems.

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2. Numerical Wave Tank

2.1 Governing equations

The schematic of a 2-D numerical wave tank is shown in Fig. 1. The propagating waves are generated by the wave maker plate at the left end, and an opening boundary is set at the other end.

The governing equations are the continuity equation and RANS equations for an impressible fluid:

$$\frac{\partial u_i}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial u_i}{\partial t}+u_i\frac{\partial u_i}{\partial x_i}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+f_{x_i}+\frac{\partial}{\partial x_j}[\upsilon\frac{\partial u_i}{\partial x_j}-\overline{u_i'u_j'}] \tag{2}$$

where x_i, u_i represent the coordinate directions and corresponding velocity components; $\rho, p, \upsilon, f_{x_i}$ are the fluid density, the fluid pressure, the kinematic viscosity coefficient, and the body force, respectively.

The component $\overline{u_i' u_j'}$ defined as the Reynolds stress induces a new turbulence model to close the equations. The standard $k-\epsilon$ model widely used in engineering application, is employed in this study to demonstrate the turbulence effect in the wave motion.

The tracking of the interface between the air and water phases is accomplished by the volume of fluid (VOF) method. In addition, the face fluxes through the computational cells are obtained using the geometric reconstruction approach. The interface between the two fluids is calculated by the piecewise-linear scheme, which assumes a linear slope in each cell.

2.2 Numerical solutions

The regular linear wave is employed in the investigation of this paper, and the motion of the piston wave maker is determined from the following equation

$$x(t) = \frac{S_0}{2}\left(1 - e^{-\frac{5t}{2T}}\right)\sin\omega t \tag{3}$$

where S_0 is the maximum displacement of the wave maker; T is the period of the incident wave, and $\omega = 2\pi/T$. On the opening boundary, the Sommerfeld radiation boundary condition will be performed for the linear wave absorption.

The motion of the wave generating and absorbing boundaries can be achieved by defining UDF (user-defined function) programs. Fluent also provides the layering remeshing method in dynamic mesh model to govern the mesh reconstruction adjacent to the moving boundaries. The geometry and meshes are created by the grid generation software Gambit 2.2.30, and it should be noted that the grids at the interface have been refined to precisely predict the free water surface.

The governing equations are solved by using the finite volume method. Second-order upwind discretization is considered for the convection terms. The pressure-velocity coupling is calculated by the NITA (Non-iterative time advancement) - PISO (Pressure implicit with splitting of operators) algorithm compatible with the VOF model, which requires only one global iteration per time step, and reduces solution time significantly.

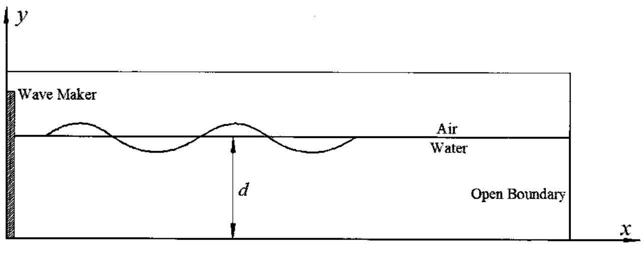

Fig. 1 Schematic of numerical wave tank

In Fluent, the symmetry definition is applied for the wave making and absorbing boundaries. The bottom is set as the wall using no-slip conditions. The pressure outlet is considered for the upper boundaries of the computational domain adjacent to the air phase.

2.3 Validation of wave tank

A rectangular wave tank with a flat bottom is set up to validate the capability of the numerical model described in this paper. The tank length is 200 m, and the water depth is 16 m. The maximum displacement of the wave maker S_0 is 0.8 m, and the incident wave period T is 3.5 s. The calculating time step is taken as 0.001 s.

Fig. 2 illustrates the computation for the wave profile distribution along the tank at t= 24 T. The results obtained by the present method show fairly good agreement with the linear wave analytical solutions. It also can be found that the wave elevations in the numerical prediction are slightly smaller in magnitude than the analytical solutions as the wave propagates in the tank. This difference can be explained by the induced turbulence model in the simulation.

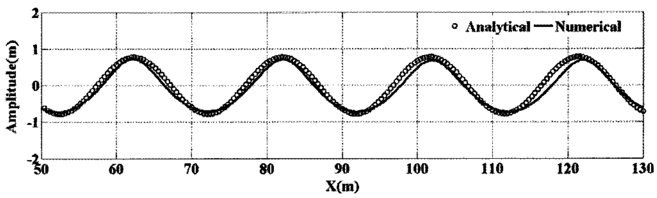

Fig. 2 Comparison of wave profile at t = 24 T

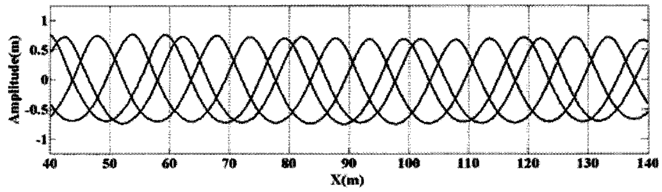

Fig. 3 Distribution of wave profiles in one period

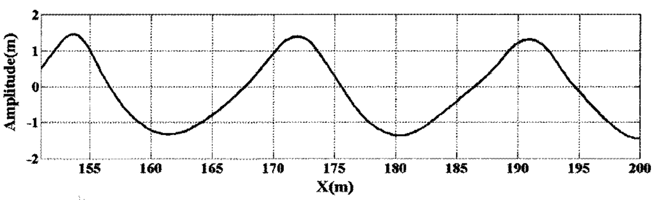

Fig. 4 Standing wave profile in front of the vertical wall

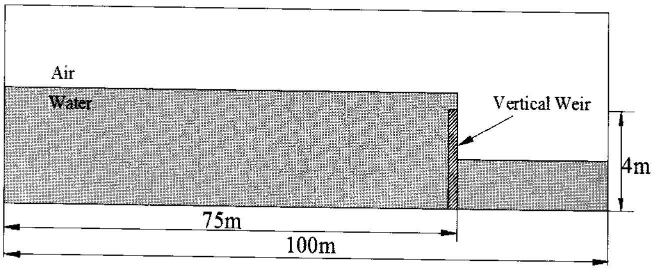

Fig. 5 Initial condition of free surface over the vertical weir

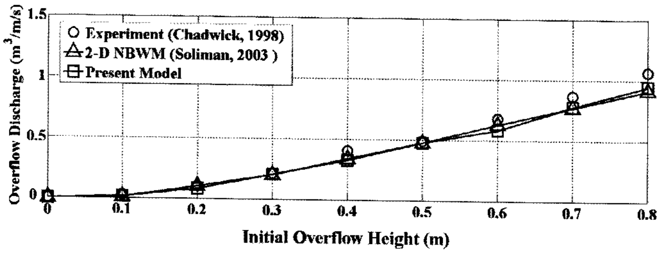

Fig. 6 Comparison of overflow discharge for vertical weir

The distribution of wave profiles at difference times in one period along the wave tank are plotted with 1 s time intervals in Fig. 3. It is demonstrated that the present numerical wave tank can be applied to generate propagating waves for a long time.

It has been reported that the reflection of some coastal structures will create standing waves with the incident waves. The wave absorbing boundary is replaced by a vertical wall to simulate these standing waves. Figure 4 displays the wave profile in front of the vertical wall. The wave amplitude is about two times higher than that of the incident wave, which illustrate that the current numerical wave tank also can provide the desired standing waves in front of the vertical wall.

All of the above numerical results indicate that the 2-D numerical wave tank developed in this paper can generate the propagating regular waves for engineering applications.

3. Testing Problem and Results

3.1 Vertical weir overflow

The overflow of a vertical weir is a useful testing benchmark. In this test, a rectangular computational domain with the length of 100 m is set. The vertical weir is located 75 m from the left end. The height of the weir is 4 m with a width of 1 m. As shown in Fig. 5, a water column with the free surface higher than the weir top is assumed. In Fig. 6, using various initial heights, calculations are made for the overflowing the weir.

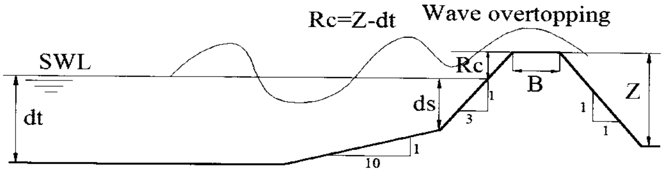

Fig. 7 Sketch of wave overtopping at sloping walls

The overflow discharges for various initial overflow heights are compared with the experimental data (Chadwick and Morfett, 1998) and former numerical results (Soliman et al., 2003). It can be seen that the calculated results of the present model shows good agreement with those obtained by Soliman et al. (2003), and slightly underestimates the overflow discharges compared with the experimental data. In general, the present numerical model shows its capability for the tracking of free water surface.

3.2 Wave overtopping at sloping sea walls

A small-scale laboratory test for wave overtopping at sloping sea walls was carried out by Saville (1998). The experiments were based on regular waves overtopping a sloping sea wall with slopes of 1:3 and 1:10. Kobbayashi and Wurijanto (1989) and Hu et al. (2000) utilized these data to validate their numerical model.

The profiles of the tested sea walls are given in Fig. 7, where d_t, and d_s represent the water depth of the still water surface (SWL) at the seaward boundary, and the water depth below the SWL at the toe of the structure and R_c represents the crest level of the structure above SWL. The configurations for 10 cases are shown in Table 1. H_t and T are the incident wave height and period, respectively.

The procession of wave overtopping at the sloping wall is illustrated in Fig. 8. It can be seen that when

Table 1 The configuration of sea walls and incident wave conditions

Case	*dt*(m)	*ds*(m)	*Rc*(m)	*Ht*(m)	*Ts*(s)
1	3.0	0.75	0.50	0.95	4.73
2	3.0	0.75	1.00	0.95	4.73
3	3.0	1.50	0.50	0.95	4.73
4	3.0	1.50	1.00	0.95	4.73
5	4.0	2.00	0.67	0.99	6.55
6	4.0	0.75	0.50	1.08	7.98
7	4.5	0.75	1.00	1.06	7.98
8	4.0	0.75	1.50	1.08	7.98
9	4.0	1.50	0.50	1.08	7.98
10	4.0	1.50	1.00	1.08	7.98

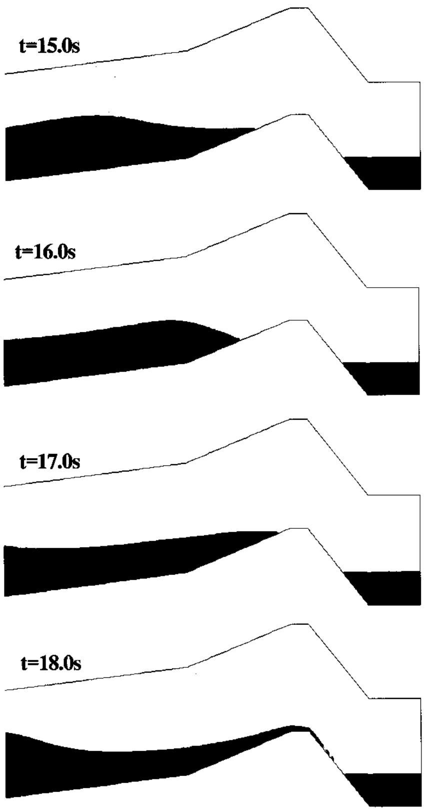

Fig. 8 Wave overtopping at the sloping wall (case 3)

the wave crest arrives at the toe, it will break while climbing the sloping wall and the water will overflow the top of structure. The numerical results demonstrate that the present model can predict the wave breaking and overtopping phenomenon for the engineering application.

The numerical and experimental results of the overtopping discharge are compared in Table. 2. The dimensionless discharge Q was defined by Kobayashi and Wurijanto (1989) as:

Table 2 Comparison of overtopping discharge at sloping wall

Case	K&W Q (10^{-3})	Amazon Q (10^{-3})	Saville Q (10^{-3})	Present Q (10^{-3})
1	27	39	66	55
2	3	15	41	27
3	53	81	64	52
4	14	24	36	41
5	81	86	90	71
6	54	64	60	58
7	16	27	17	22
8	2	11	4	9
9	91	101	94	100
10	45	53	40	40

$$Q = \frac{Q'}{H_0\sqrt{gH_0}} \tag{4}$$

where Q' is the dimensional average overtopping discharge. The dimensionless wave height H_0 is transformed from the H_t by the use of the linear shoaling theory (Goda, 1985). In order for the results to be consistent with the former numerical results, an averaged value of Q is calculated during the fourth and fifth wave.

When comparing results produced by the present model with the experimental and former simulated results, it is found that the present computational predictions agree well with the laboratory data, and are more accurate than the former numerical models.

4. Conclusions

A 2-D fluent-based numerical wave tank (FBNWT) was established in this paper. The present numerical model uses the Reynolds averaged Naiver-Stokes equations and VOF model. The NITA-PISO algorithm and dynamic mesh method were employed for wave generation and propagation, which has been validated by the analytical solutions.

The overflow of a vertical weir and wave overtopping at sloping seawalls were simulated by the 2-D FBNWT to investigate the capability of the present numerical model in relation to wave overtopping. A comparison with the experimental and former numerical results demonstrated that the FBNWT is capable of predicting wave propagating and overtopping for engineering applications.

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