CHAPTER 169

A Viscous Rotational Model for Wave Overtopping over Marine Structure

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Abstract

Wave overtopping problems continue to require more attention due to the complexity of the physical process and the lack of available predictive models. In a recent experimental study on the kinematics of wave overtopping on marine structure by Lee, Zhuang and Chang (1993), it was found that the overtopping wave constitutes a jet-like water mass impacting the shoreward region of the breakwater. This jet-like water mass induces strong vortices and large water particle velocities in both the horizontal and vertical direction in the shoreward region behind the marine structure. The large rotational velocity field is capable of removing the armor units of the breakwater and scouring the bed in the shoreward region of the breakwater. In the study of Zhuang, Chang and Lee (1994), a numerical model capable of generating the rotational velocity field in the vicinity of the shoreward face of the breakwater was proposed. This paper presents the computation results from a refined viscous rotational model and their comparisons with newly acquired experimental data.

1. Introduction

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Overtopping of ocean waves over marine structures has been an important problem for ocean and coastal engineers due to the fact that it may severely damage the marine structure. The overtopping process may transmit significant wave energy toward the coastal zone which the marine structure (such as breakwater) is supposed to protect.

In a recent experimental study on the kinematics of wave overtopping on marine structure by Lee, Zhuang and Chang (1993), it was found that the overtopping wave constitutes a jet-like water mass impacting the shoreward region of the breakwater. This jet-like water mass induces strong vortices and large water particle velocities in both the horizontal and vertical direction. Moreover, the overtopping wave also generates waves in the shoreward region possessing significant wave energy with oscillatory wave trains. These two major conclusions have significant practical implications: The large rotational velocity field can remove the armor units of the breakwater and scour the bed. The generated waves could induce significant basin oscillations in the shoreward basin with resonant frequencies which are different from the incident wave frequencies. Such experimental results deviated significantly from the potential flow theory in certain regions. Thus, computational results based on the potential flow theory can not fully explain the experimental data without incorporating additional features. In the study of Zhuang, Chang and Lee (1994), a numerical model capable of generating the rotational velocity field in the vicinity of the shoreward face of the breakwater was proposed. This paper presents the computation results from a refined viscous rotational model and their comparisons with newly acquired experimental data.

2. Experiments

Experiments involving propagation of solitary waves over various submerged breakwater configurations are conducted in a wave tank 37.73 meter long, 39.4 centimeter wide, and 61 centimeter deep. A programmable piston type wave generator is installed at one end of the tank and a sloping beach is installed at the other end of the tank to aid the wave dissipation for the purpose of reducing the waiting time between experimental runs. Three different breakwater configurations are used in the experiment. Three resistance type wave gauges are installed at desired locations to make simultaneous wave profile measurements.

The water particle velocities are measured using a portable four-beam, two-component, fiber optic Laser Doppler Velocimeter (LDV) manufactured by TSI Inc.. Titanium Dioxide powder (TiO_2) is used in the experiments as a seeding agent.

3. Numerical Models

The refined viscous rotational flow model consists of two basic elements: The velocity field generated by using the potential flow theory and the rotational velocity field generated by the separated flow (vortices) of the overtopping waves as they leave the breakwater site. For the potential flow theory, the Boundary Element Method has been used. The nonlinear boundary condition at the free surface is satisfied in the numerical model to allow simulation of large amplitude waves. The transient non-rotational flow field obtained by the potential flow theory is combined with the time dependent rotational flow field due to vortices generated in the separation zone.

The potential flow theory formulation using boundary element method has been presented in Lee, Chang and Zhuang (1992). The problem of wave overtopping on marine structure is formulated as a two-dimensional boundary value problem. The fluid in the solution domain is assumed to be incompressible and the flow is assumed to be irrotational. Viscous force is also neglected. Application of potential theory leads to the governing Laplace's equation for the velocity potential function ϕ:

$$\nabla^2\phi(\mathbf{x},t) = 0 \qquad\qquad \mathbf{x} \in \Omega(t) \tag{1}$$

with the kinematic and the nonlinear dynamic free surface conditions as the boundary conditions on the free surface Γ_s:

$$\frac{D\mathbf{r}}{Dt} = (\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla)\mathbf{r} = \mathbf{u} = \nabla\phi \tag{2}$$

$$\frac{D\phi}{Dt} = -gy + \frac{1}{2}|\nabla\phi|^2 - \frac{p_a - p_o}{\rho} \tag{3}$$

where $\mathbf{r}$ is the position vector of a free surface fluid particle, g the acceleration due to gravity, y the vertical coordinate, p_a the pressure at the surface, p_o a reference pressure and ρ the fluid density.

The solution to the boundary value problem is expressed as a boundary integral using the free space Green's function $G(\mathbf{x}_i,\mathbf{x}_j) = -\frac{1}{2\pi}\log|\mathbf{x}_i - \mathbf{x}_j|$ and Green's theorem:

$$\alpha(\mathbf{x}_i)\phi(\mathbf{x}_i) = \int_{\Gamma(\mathbf{x})}\left[\frac{\partial\phi}{\partial n}G(\mathbf{x},\mathbf{x}_i) - \phi(\mathbf{x})\frac{\partial G(\mathbf{x},\mathbf{x}_i)}{\partial n}\right]d\Gamma(\mathbf{x}) \tag{4}$$

where $\mathbf{x}_i$ and $\mathbf{x}$ are position vectors for points on the boundary ($\mathbf{x}_i$ can also be any where within the domain), $\Gamma(\mathbf{x})$ is the boundary of the fluid domain Ω, $\mathbf{n}$ the unit outward normal vector and $\alpha(\mathbf{x}_i)$ a geometric coefficient. The boundary integral equation is then solved using the Boundary Element Method.

A time marching procedure which was first suggested by Dold and Peregrine (1986) has been used in the present analysis to update both the new position of the free surface and the potential value ϕ on the free surface at the next time step:

$$\mathbf{r}(t+\Delta t) = \mathbf{r}(t) + \sum_{k=1}^{n} \frac{(\Delta t)^k}{k!} \frac{D^k \mathbf{r}(t)}{Dt^k} + O[(\Delta t)^{n+1}] \tag{5}$$

$$\phi(\mathbf{r}(t+\Delta t), t+\Delta t) = \phi(\mathbf{r}(t), t) + \sum_{k=1}^{n} \frac{(\Delta t)^k}{k!} \frac{D^k \phi(\mathbf{r}(t), t)}{Dt^k} + O[(\Delta t)^{n+1}]. \tag{6}$$

The Boundary Element Method together with the time marching procedure form a unique solution technique for solving transient nonlinear wave problems.

The rotational flow field in the vicinity of the shoreward breakwater is simulated with the governing equations for the vorticity stream function formulation of incompressible laminar flow. Figure 1 shows the computational domain for this rotational flow field (ABCDE). The governing equations are:

$$\frac{\partial \omega}{\partial t} + u\frac{\partial \omega}{\partial x} + v\frac{\partial \omega}{\partial y} = \nu\left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2}\right) \tag{7}$$

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = \omega \tag{8}$$

where ω is the vorticity vector; u,v are the horizontal and vertical components of the velocity vector, and ν is the kinematic viscosity of the fluid. The boundary conditions in conjunction with the governing equations (7) and (8) are listed as follows:

A-B and A-E:

$$u = 0, \quad v = 0, \quad \psi = 0$$

B-C:

$$\frac{\partial \psi}{\partial y} = u, \qquad \omega = \frac{\partial u}{\partial y} - \frac{\partial v}{\partial x}$$

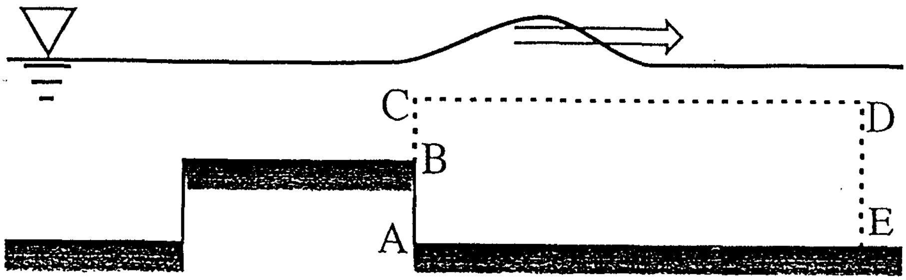

Figure 1: Sketch of the computational domain.

C-D:

$$\frac{\partial \psi}{\partial x} = -v, \qquad \omega = \frac{\partial u}{\partial y} - \frac{\partial v}{\partial x}$$

D-E:

$$\frac{\partial \omega}{\partial x} = 0, \qquad \frac{\partial^2 \psi}{\partial x^2} = 0$$

For each time step, the particle velocity solution is collected along B-C and C-D from the computational results based on the boundary element method (potential flow theory). These are used as the boundary conditions for the vorticity stream function formulation, hereafter we refer it as combined rotational model. Equation (8) is solved using Successive Over Relaxation method. Equation (7) is then solved using Alternating Direction Implicit method. The same computational procedure is repeated over the successive time steps. For detailed description of the numerical model, the reader is referred to Zhuang (1996).

For the two dimensional wave overtopping problem, potential theory with boundary element method has shown to have the following advantages: (1) the boundary element method can reduce the dimension of the original problem by one, thus reduce the computer storage requirements and speed up the computation. (2) the boundary element method is especially suitable for problems where the variables of primary interest are mainly located on the boundary, such as wave-related problems. (3) it has been proved by previous study (Lee, Chang and Zhuang (1992)) that potential theory results agree well with the experimental data for the region near the free surface and the region far away from the separation zone near the breakwater. But, it is also shown through the present experimental data that in the separation zone (where vortex generation and large induced flow velocities are prevailing) potential theory can not be valid.

As for the vorticity stream function formulation with finite difference method, it includes elements of rotationality and viscous effect, and it can be used to describe flow separation and vortex generation. However, this formulation is difficult in dealing with free surface calculation and is not economical in terms of computational cost compared with the boundary element method.

In order to make the numerical model capable of simulating the whole wave overtopping process, and to take advantages of both the potential flow theory and the vorticity stream function formulation, the present study proposes a combined numerical model. In this model, potential flow theory with boundary element method is used to obtain the wave profile and flow field information in the region where the flow can be assumed inviscid and irrotational, i.e. the region near the free surface and the region far away from the separation zone. In the region near the shoreward breakwater, where flow separation and vortex generation are dominant, vorticity and stream function formulation is employed to capture the rotational flow motion in this region.

It is reasonable to expect that the computational results from the boundary element method based on the potential flow theory would fail at the separation zone due to its imposed assumption of inviscid fluid and irrotational condition. However, the computational results should be reasonably valid in the region far away from the separation zone. Therefore, our modeling strategy for the region near the separation zone is adopted as follows: As the incident wave propagates over the breakwater, the computed velocity field from the boundary element method in the regions BC and CD are used as input boundary condition for the rotational flow simulations based on equations (7) and (8). In this approach, the domain of computation is fixed thus the computational effort is greatly simplified.

4. Results and Discussion

During the experiment we have observed flow separation and vortex generation near shoreward face of the breakwater. These observed phenomena and the inability of the potential flow theory to describe the flow phenomena motivated the development of the present combined rotational flow model. In this section, the focus will be in the separation zone. Flow patterns, detailed particle velocity time history obtained from both the experiments and the present combined rotational flow model will be presented.

Figure 2 and 3 present a series of four photographs taken during one experimental run of H/d=0.3 solitary wave overtopping on submerged Breakwater C (hight=4.5in and width=15in) with water depth d=9in. The blue dye is injected in the shoreward region of the breakwater before the wave is generated. The solitary wave propagates from left to right direction in the pictures. The breakwater can be seen at the lower left corner of the pictures. From Figure 2(A), we can see a vortex is starting to form at the shoreward edge of the breakwater while the wave crest is approximately on the top of the edge. The following three pictures show a complete process for the generation of a vortex. It is observed that a strong rotational flow field has been generated in the vicinity of the shoreward breakwater. Since this is a transient process, the vortex will grow bigger and bigger after the wave has passed and eventually move downstream and become disintegrated. A practical point to remember is that the rotational field so generated will induce more scouring capability in the shoreward region of the breakwater.

The velocity time history comparisons between the model results and the experimental data are presented in Figures 4 and 5. Figure 4 shows the velocity time history at a location P-825. The location P-825 is at the vertical position -0.825d from the still water surface and 0.15d from the breakwater shoreward surface. Included in the figure are the results of the potential flow theory (solution from boundary element method) shown in solid line. The results from the combined rotational flow model are shown in dotted line. The velocity time history obtained by using the Laser Doppler Velocimeter measurement are plotted using the star symbols. The ordinates in both figures are the velocity components normalized with respect to $\sqrt{gd}$ (the wave celerity in water depth d). The abscissa is the real time normalized as $t\sqrt{g/d}$. Examining both the horizontal and vertical velocities, it is seen that, at location P-825, both the combined rotational flow model and experimental data reveal that the horizontal velocity changes direction from positive to negative and the vertical velocity changes the direction from negative to positive. That means the flow direction at that point changes from forward and downward to backward (seaward) and upward. It clearly shows that a vortical motion has been generated during the wave overtopping process.

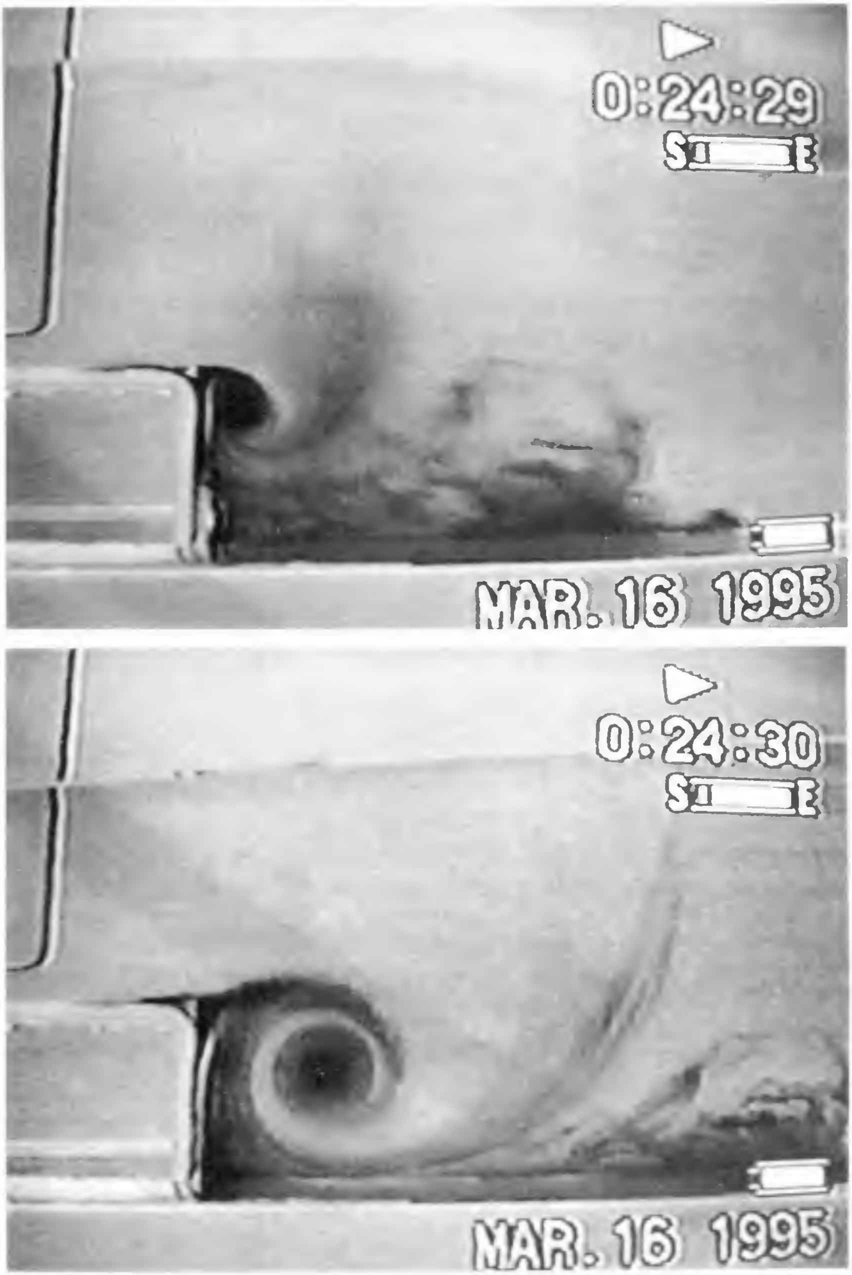

Figure 2: Pictures (A) and (B) of an experimental observation of vortex generation for solitary wave overtopping submerged breakwater. H/d=0.3, d=9in, Breakwater C.

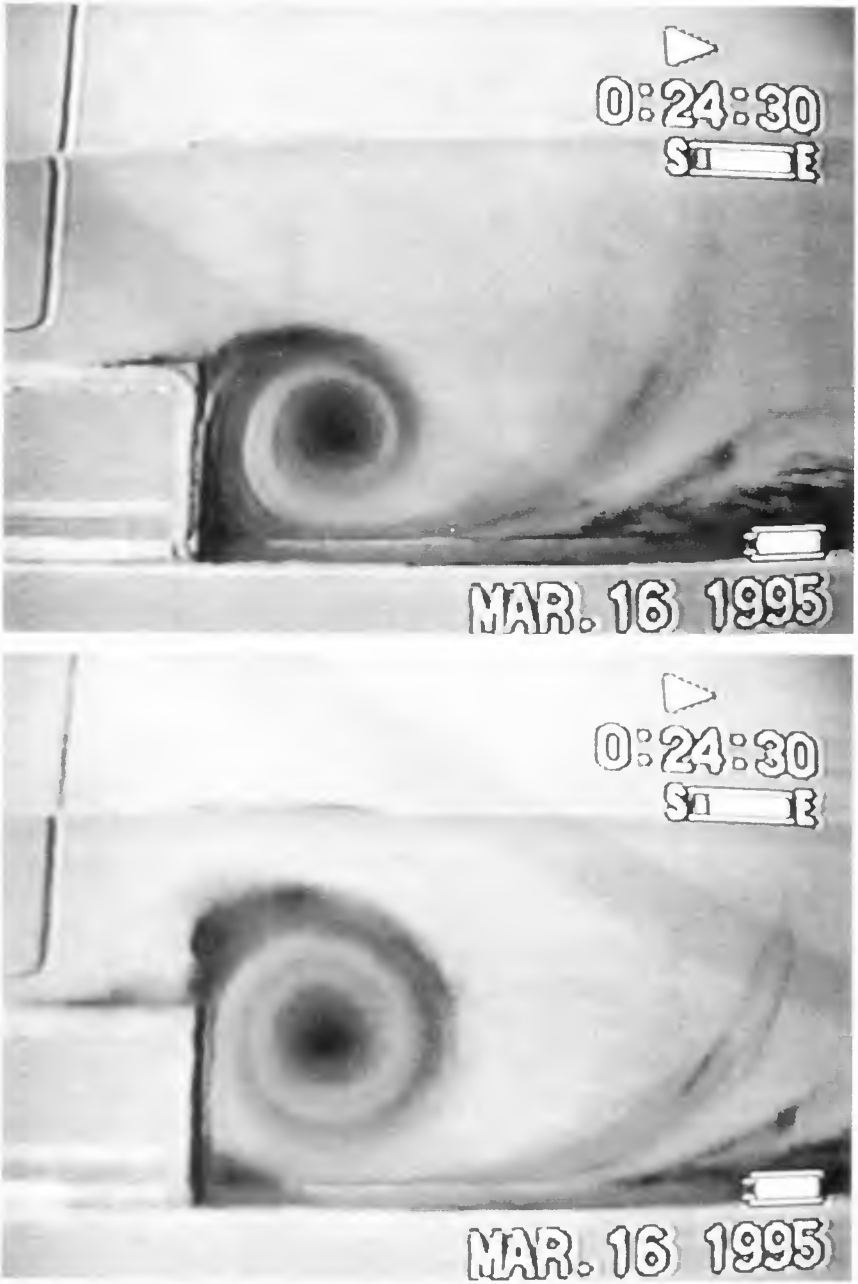

Figure 3: Pictures (C) and (D) of an experimental observation of vortex generation for solitary wave overtopping submerged breakwater. H/d=0.3, d=9in, Breakwater C.

The present combined rotational flow model predicts this feature of particle movement and agree well with the experimental data. As expected, the potential theory predicts only positive horizontal velocity and negative vertical velocity. The results from the potential flow model deviate significantly from the experimental data beyond a very short time after the arrival of the waves. Thus, according to the potential flow theory, the particles are always going forward and downward directions during the overtopping process, representing no rotational motion. It is reasonable to expect that the computational results from the boundary element method based on the potential flow theory would fail in the separation zone due to its imposed assumption of inviscid fluid and irrotational condition.

Another noticeable feature to be observed from this time history graph is the magnitude of the positive vertical velocity and negative horizontal velocity, both are much greater than the particle velocities associated with an unmodified solitary wave. This feature of increased particle motion could contribute to the destabilization of the breakwater armor units in the shoreward face.

Figure 5 shows horizontal and vertical velocity time history comparisons between the present model and the experimental results at location P-75 for 0.3 solitary overtopping on Breakwater C. Location P-75 is -0.75d from the still water surface and 0.15d from the breakwater shoreward surface. It is 0.075d above location P-825. As observed from Figure 4, velocity at location P-75 also shows the reversal of horizontal velocity from shoreward to seaward direction and the reversal of vertical velocity from downward to upward. Although location P-75 is very close to location P-825, we can see the velocity time histories from the two locations have significant differences. It indicates that there is a rapidly changing velocity field in this region. Notice that the vertical velocity reached the maximum when the horizontal velocity becomes small, indicating location P-75 is in the middle left portion of the clockwise rotating vortex, where the flow is basicly going up. Again Figure 5 shows the results from the present rotational flow model agree quite well with experiments.

5. Conclusions

The major conclusions drawn from this study can be summarized as follows:

1. A numerical model has been developed to simulate wave induced vis-

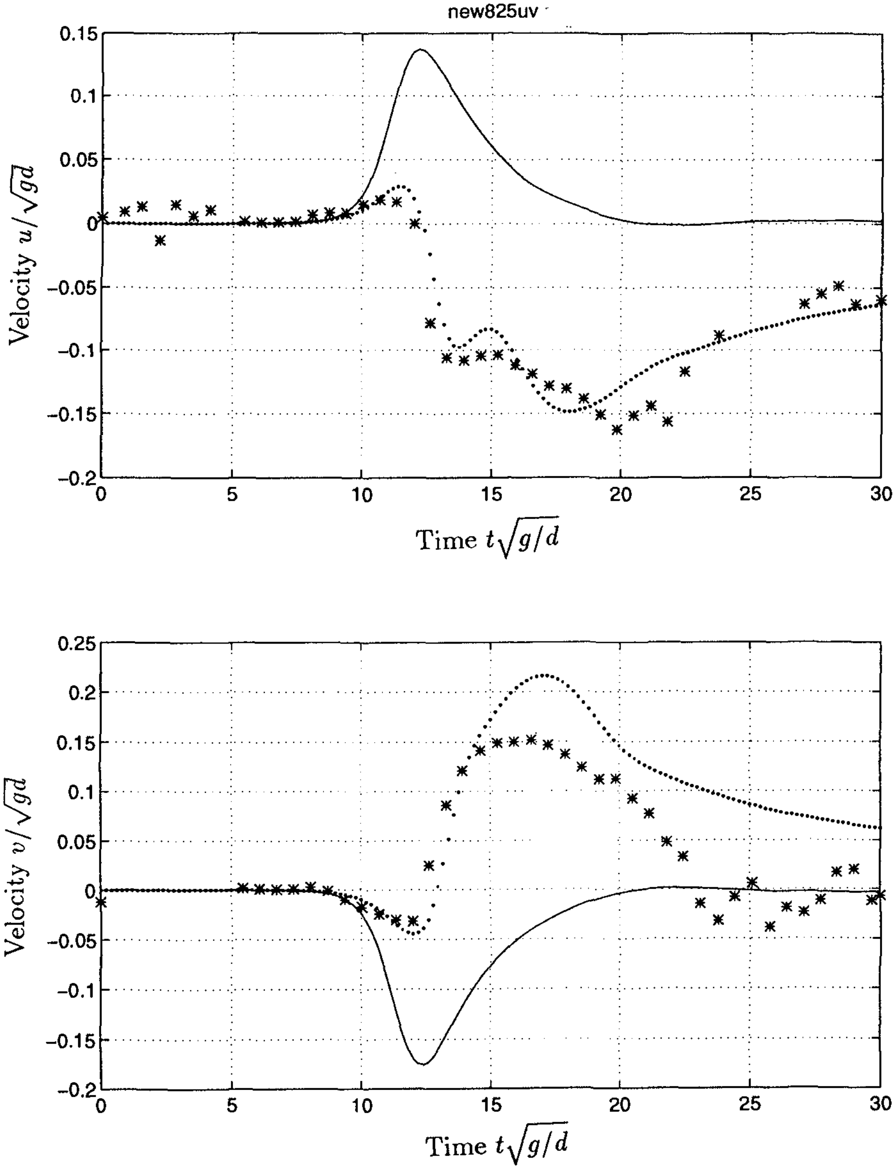

Figure 4: Comparison of particle velocity results from the present model, potential flow theory and experiment at $x^* = 0.15$ and $y^* = -0.825$ for solitary wave overtopping on breakwater C, $H/d = 0.3$, $d = 9in$; $\cdots$ present model; — potential flow model; $***$ experiment.

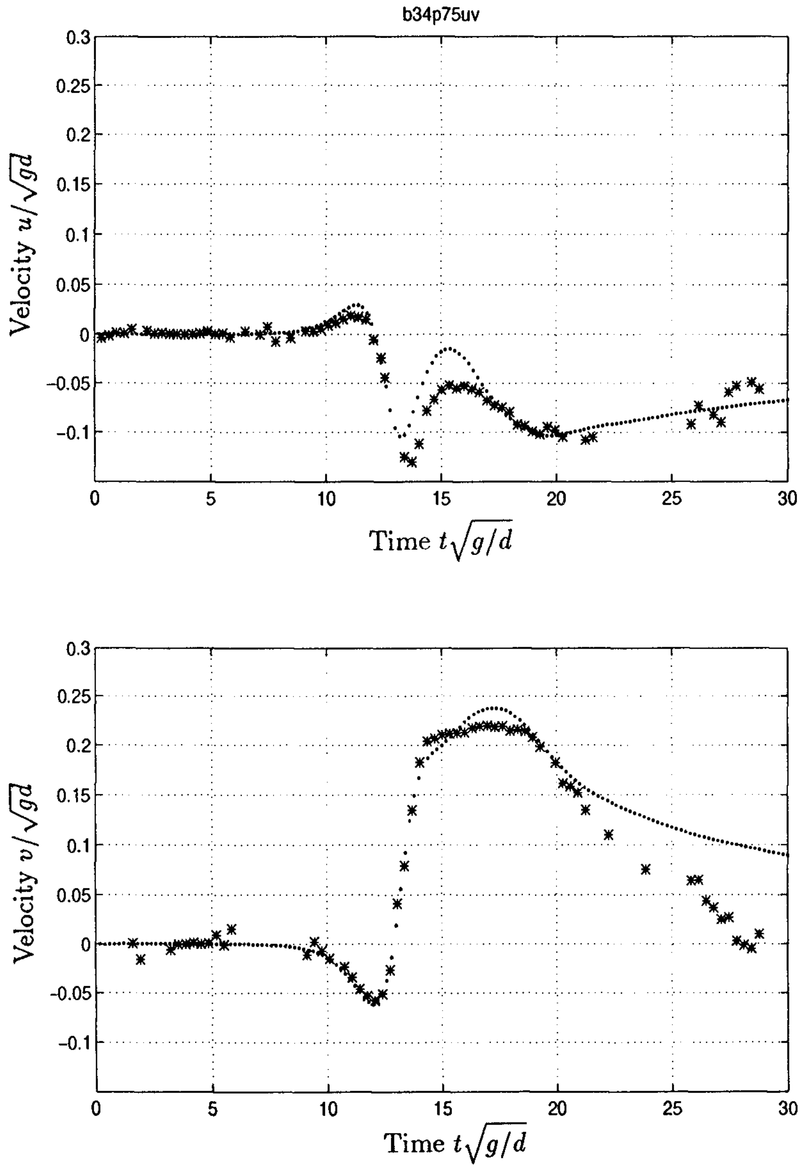

Figure 5: Comparison of particle velocity results from the present model and experiment at $x^* = 0.15$ and $y^* = -0.75$ for solitary wave overtopping on breakwater C. H/d=0.3, d=9in; ··· present model; * * * experiment.

cous rotational flow in the separation zone near shoreward breakwater surface. This model is referred as the combined rotational flow model because it combines two distinct theories and corresponding solution methods and it is capable of evaluating rotational separating flow field. It is seen that the combined rotational flow model describes the flow field quite well when compared with the experimental data. It offers a tool for modeling the flow field in the vicinity of the shoreward region of the breakwater. It is also seen that the potential flow results deviate from the experiments significantly. This demonstrates the importance of incorporating the rotational feature for modeling the flow field in the vicinity of the shoreward region of the breakwater.

2. Based on both the numerical and experimental results it is found that there is a vortex generated by the overtopping of solitary wave in the vicinity of the shoreward breakwater. The vortical motion remains there even when the wave has traveled to the region far away from the breakwater. This vortical motion produces a velocity field which could cause significant scouring in the region close to the breakwater.

3. Because of the vortex motion, there is a relatively large velocity component in the upward and seaward direction. This velocity component could produce a lifting force which could destabilize the armor units in the shoreward face of the breakwater.

4. The present combined rotational flow model can be easily implemented because of its time-saving feature. It only computes rotational flow field in a relatively small local domain, while the efficient potential theory using boundary element method offers the information away from the separation zone, where the irrotationality assumption is valid. Furthermore, this model can be extended to solve other wave-structure interaction problems.

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