CHAPTER 122

Modelling of Wave Overtopping over Breakwater

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Abstract

From 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 generates a strong rotational velocity field in the shoreward region of the breakwater. The present study focuses on the development and the implementation of a numerical model for the generated velocity field in the vicinity of the shoreward face of the breakwater. The numerical model consists of two basic elements: The velocity field generated by using the potential flow theory utilizing boundary element method and the rotational velocity field generated by the separated flow of the overtopping waves as they leave the breakwater site using vorticity stream function formulation. The computational results at a region far away from the separation zone based on the potential flow theory (boundary element method) are used as specified boundary conditions for simulation in the vorticity stream function model. The numerical results have been compared with the experimental data revealing the rotational feature of the velocity field in the separated zone (shoreward region of the breakwater). The generated vortical motion remains in the separation region even when the wave has travelled to the region far away from the breakwater.

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1. Introduction

Interaction of nonlinear waves with marine structure such as the breakwater has been an important problem for coastal and ocean engineers. Among the many aspects of the interaction problem, wave overtopping may require more attention due to the complexity of the physical process and the lack of available predictive models. When the water depth at the breakwater site is quite close to the breakwater height, and the incident wave amplitude is large, a substantial wave overtopping can be expected.

In a recent experimental study on the kinematics of wave overtopping on marine structure by Lee, Zhuang and Chang (1993) some very fascinating results have been found. 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. The present study focuses on the development and the implementation of a numerical model capable of generating the rotational velocity field in the vicinity of the shoreward face of the breakwater.

2. Experiments

Experiments involving propagation of solitary waves over various submerged breakwater configurations are conducted in a wave tank 15.2 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. Two 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

Motivated by the findings in the experiment, the present paper will focus on the development and the implementation of a numerical model for modeling the generated velocity field in the vicinity of the breakwater as well as the wave field generated by the overtopping waves. The numerical 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 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:

$$\frac{\partial \omega}{\partial t} + u\frac{\partial \omega}{\partial x} + v\frac{\partial \omega}{\partial y} = \nu \left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} \right) \tag{1}$$

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

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 conjuction with the governing equations (1) and (2) are listed as follows:

A-B and A-E:

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

B-C:

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

C-D:

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

D-E:

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

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 (2) is solved using Successive Over Relaxation method. Equation (1) is then solvd using Alternating Direction Implicit method. The same computational procedure is repeated over the successive time steps.

4. Results and Discussion

The wave profile and the velocity vector field induced by an incoming solitary wave with various wave amplitude to water depth ratio over a submerged breakwater has been computed using the boundary element method presented by Lee, Chang and Zhuang (1992). Figure 2 presents computational results for the case of H/d=0.2 for different time steps. The incident solitary wave is propagating from left to right. From Figure 2 it is seen that the transmitted waves contains oscilatory tails and the velocity field in the shoreward side of the breakwater does not show any rotational flow field based on this potential flow computation. As mentioned in Lee, Chang and Zhuang (1992) however, the experimental data agree well with the theory on the computed wave profiles and accompanying kinematics of the water particle in the region close to the free surface as well as in the region far away from the separation zone. However, the agreement between the experimental data and the results of the potential flow theory breaks down in the region near the separated zone. In fact, experimental evidence shows that as soon as the incident solitary wave passes over the breakwater, vortices are generated in the separation zone. These vortices are then formed to create a rotational flow field with both the horizontal and vertical components of the water particle velocity changing directions rapidly.

Figure 3 is a photogragh taken in the experiment. It shows the generation of a vortex at the vicinity of the shoreward step of the breakwater, after the passage of the solitary wave over the breakwater. It is observed that a strong rotational flow field has been generated and the flow direction close to the shoreward breakwater surface is upward and seaward.

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 modelling 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 (1) and (2). In this approach, the domain of computation is fixed thus the computational effort is greatly simplified.

Figure 4 presents the computed streamlines showing the process of the vortex generation at different time steps. As mentioned earlier the specific condition simulated is such that the crest of the breakwater is at one-half of the water depth. The wave hight/water depth ratio is 0.3. The breakwater width is ten times the breakwater height. The domain of simulation for rotational flow computation is AC=DE=0.8d, and AE=CD=4d, where d is the still water depth. Figure 5 is the velocity vector field plot coresponding to the streamline plot presented in Figure 4. The results show that the vortex motion will remain eventhough the wave peak has travelled away from the breakwater. These aspects of the simulated results are in agreement with the experimental observation. A practical point to remember is that the rotational field so generated will induce more scouring capability in the shoreward region of the breakwater.

Figures 6 and 7 show the velocity time history at a location P (as indicated in the definition sketch included in Figure 1). The location P is at the vertical position one-half of the breakwater height and one-tenth of the depth 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 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 Figure 6 and 7, it is seen that, at location P, both the combined rotational model and experimental data reveal that the horizontal velocity changes direction from positive to negative and 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. The present combined rotational model predicts this feature of particle movement and agree qualitatively well with the experimental data. As expected, the potential theory predicts only positive horizontal velocity and negative vertical velocity. Thus, according to the potential flow theory, the particles are always going forward and downward directions during the overtopping process, representing no rotational motion. The magnitude differences between the present model and the experimental data in the early stages of flow could be caused by the minor geometry differences of the breakwater (the experimental model breakwater has a slight slope at both seaward and shoreward side). Since the absolute value of the present model is smaller than the experimental data at the early stages of flow, it might be that the model computation was still warming up at the time. We plan to conduct more experimental measurements using the physical model breatwater with the exact geometry as the computation model. Another noticeable feature from the time history graph is the magnitude of the positive 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.

5. Conclusions

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

1. The combined potential flow theory and vorticity stream function formulation model describes the flow field quite well based on the comparison with the experimantal data. It offers a tool for modelling the flow field in the vicinity of the shoreward region of the breakwater.

2. 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 travelled 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 could produce a lifting force which could destabilize the armor units in the shoreward face of the breakwater.

4. The present combined rotational model can be easily implemented because of its time-saving feature. It only computes rotational flow field in a relativelysmall 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.

Acknowledgment

This study is supported by USC Foundation for Cross-Connection Control and Hydraulic Research. The LDV System is supported by NSF under Grant No. 8906898. The authors are grateful for the generosity of Dr. Fredric Raichlen for permitting them to conduct the experiments at Caltech's W.M. Keck Laboratory of Hydraulics and Water Resources.

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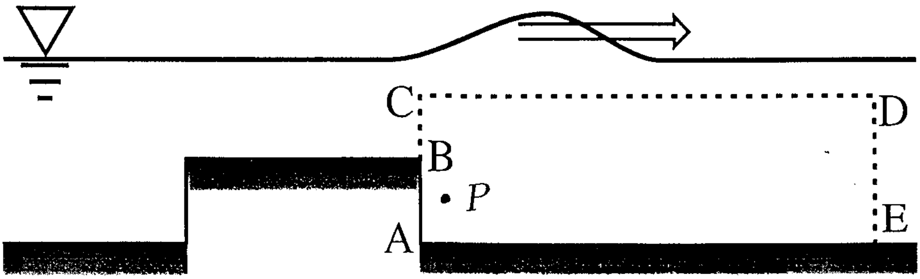

Figure 1: Sketch of the computational domain.

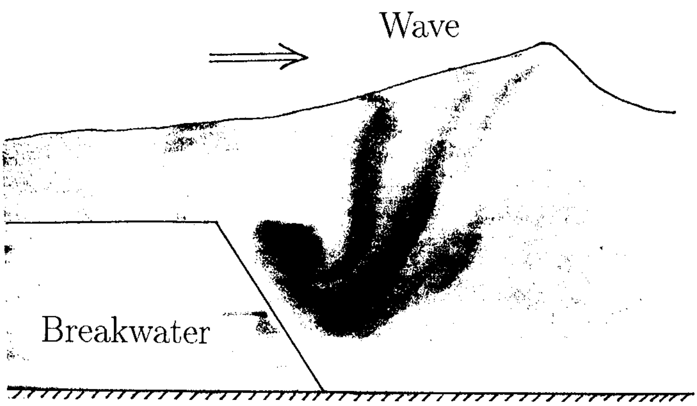

Figure 3: Photograph showing vortex generation by solitary wave propagating over a model breakwater in the experiment

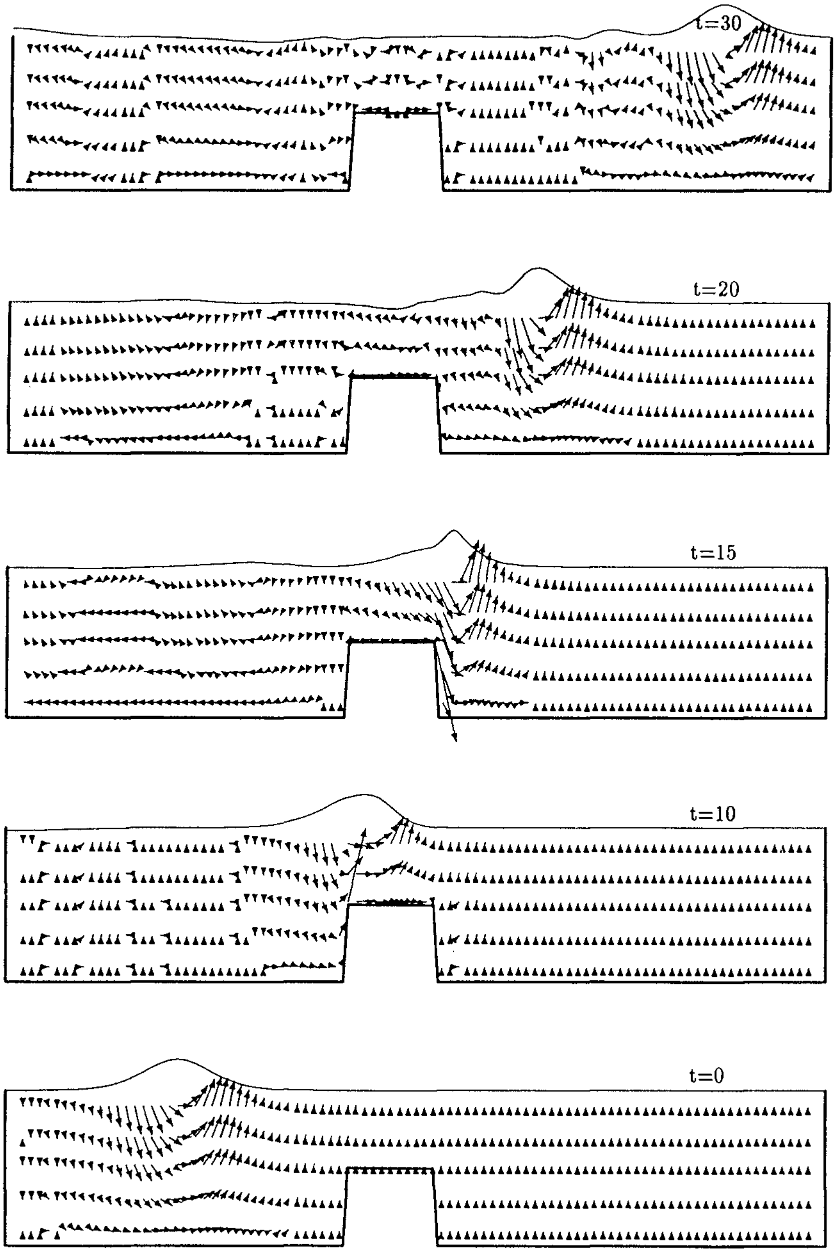

Figure 2: Velocity vector field at five time instants for the case of H/h=0.2 solitary wave (based on the boundary element method of Lee, Chang and Zhuang (1992))

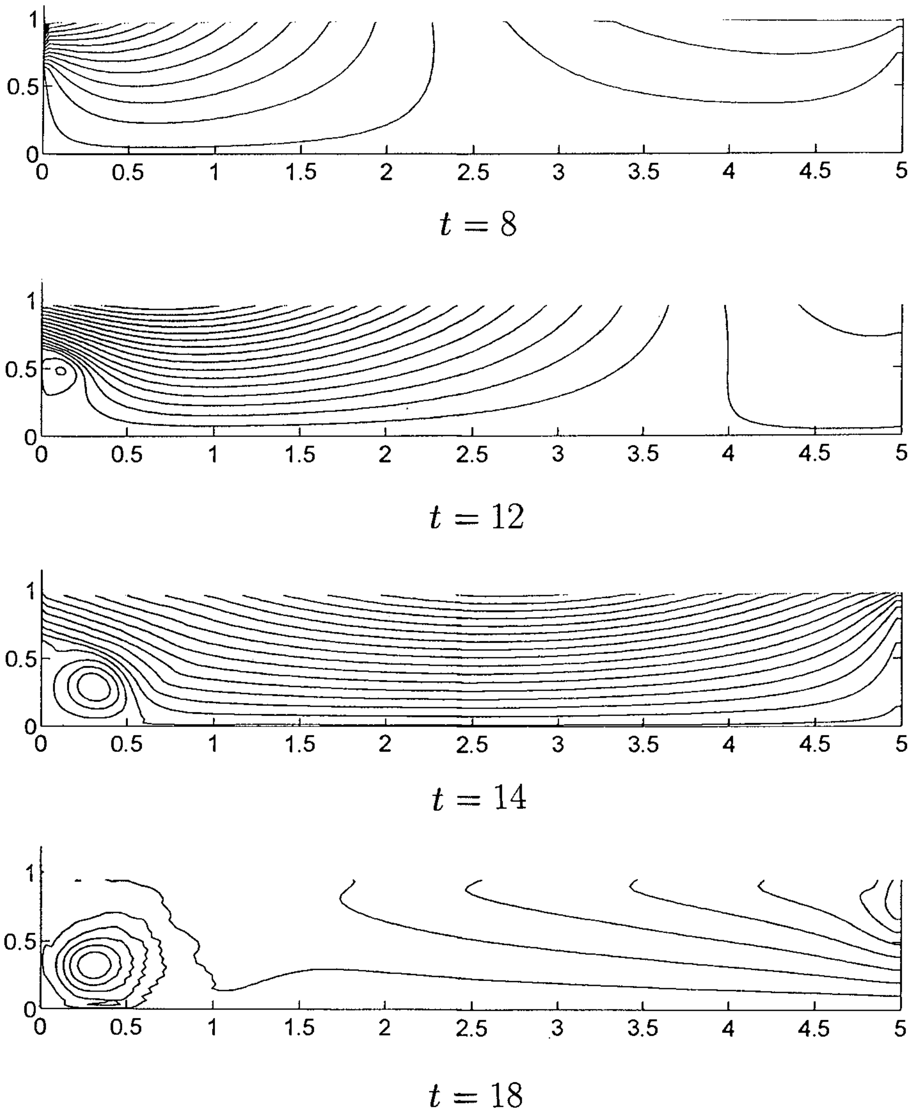

Figure 4: Streamlines at different time steps by the present model.

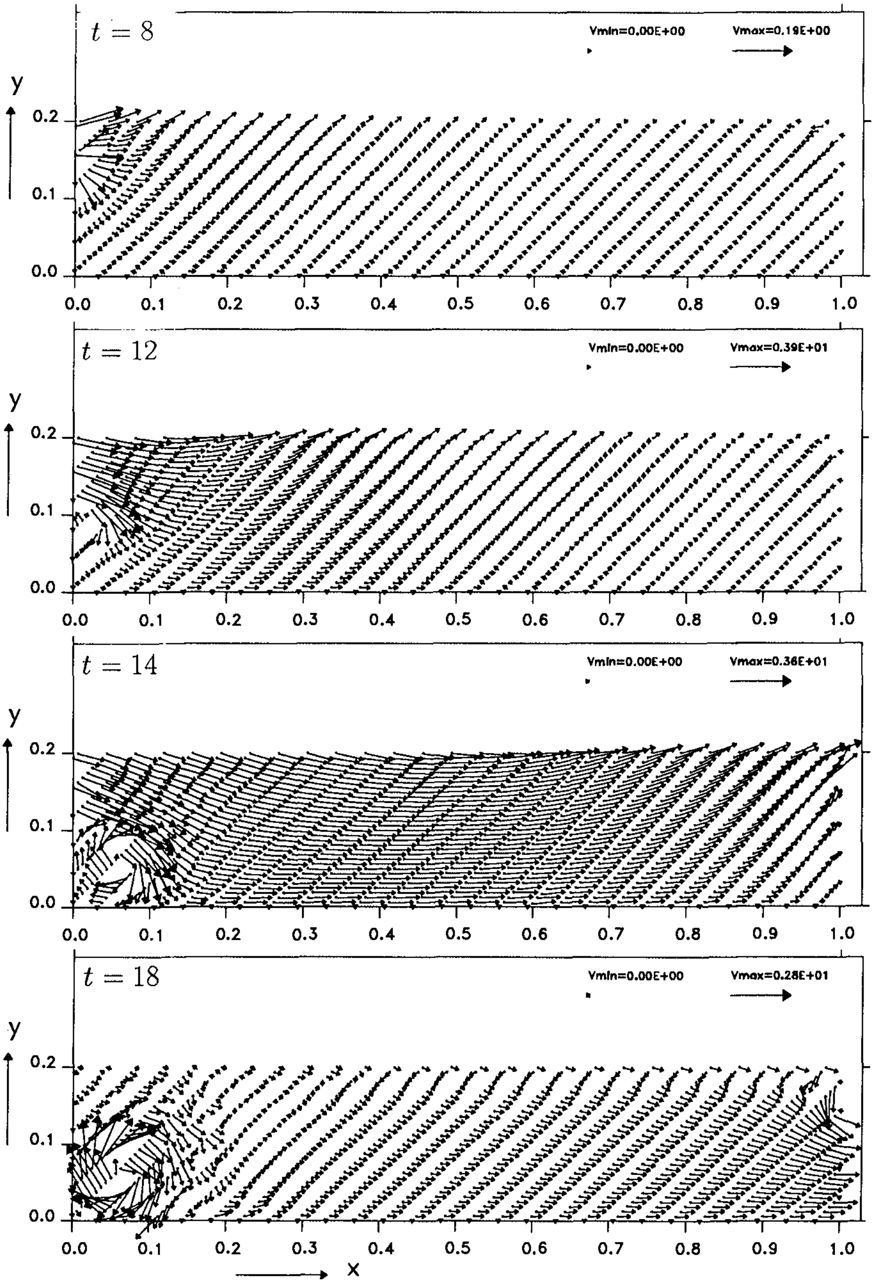

Figure 5: Velocity vector field at different time steps by the present model.

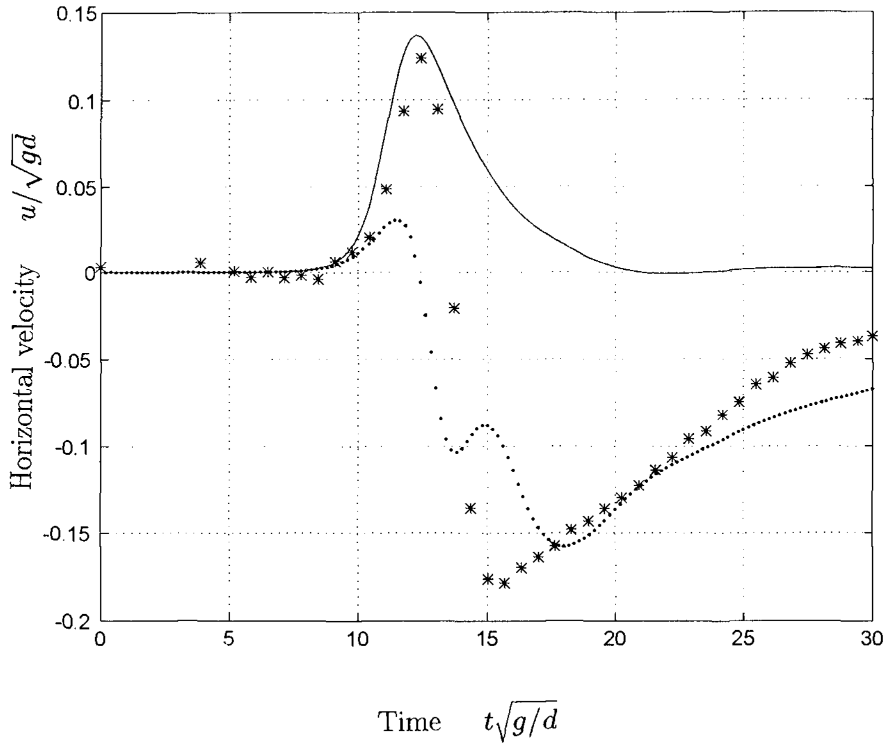

Figure 6: Comparison of horizontal water particle velocities at location P near the surface of the shoreward breakwater. The breakwater hight to water depth ratio is 0.5 and the solitary wave height to water depth ratio is 0.3.

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——— potential flow theory using boundary element method;

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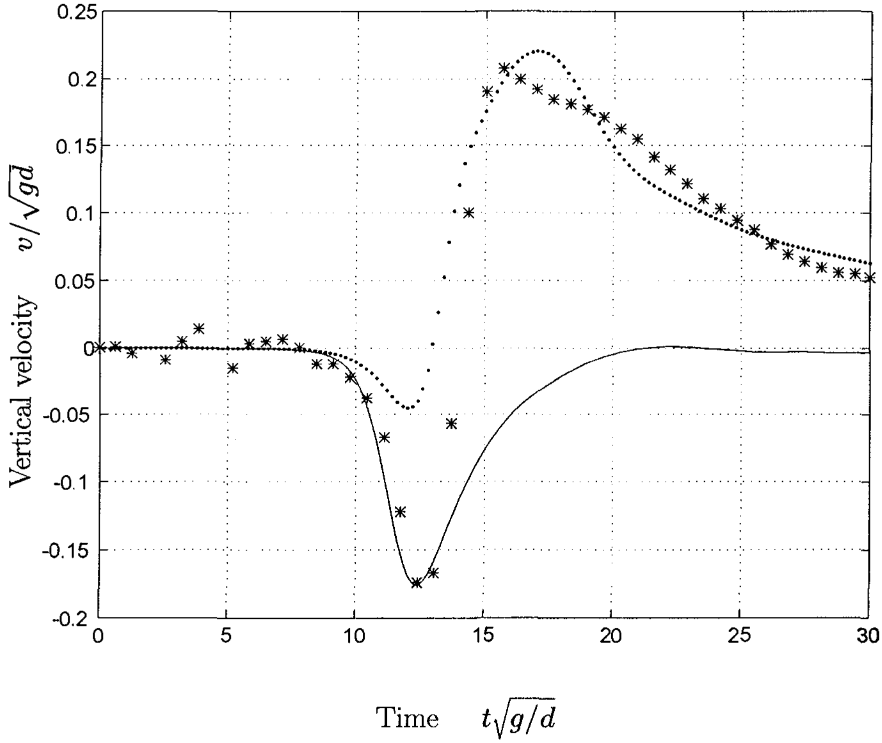

Figure 7: Comparison of vertical water particle velocities at location P near the surface of the shoreward breakwater. The breakwater hight to water depth ratio is 0.5 and the solitary wave height to water depth ratio is 0.3.

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