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Boundary layer approach in the modeling of breaking solitary wave runup

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ABSTRACT

The boundary layer is very important in the relation between wave motion and bed stress, such as sediment transport. It is a known fact that bed stress behavior is highly influenced by the boundary layer beneath the waves. Specifically, the boundary layer underneath wave runup is difficult to assess and thus, it has not yet been widely discussed, although its importance is significant. In this study, the shallow water equation (SWE) prediction of wave motion is improved by being coupled with the k–ω model, as opposed to the conventional empirical method, to approximate bed stress. Subsequently, the First Order Center Scheme and Monotonic Upstream Scheme of Conservation Laws (FORCE MUSCL), which is a finite volume shock-capturing scheme, is applied to extend the SWE range for breaking wave simulation. The proposed simultaneous coupling method (SCM) assumes the depth-averaged velocity from the SWE is equivalent to free stream velocity. In turn, free stream velocity is used to calculate a pressure gradient, which is then used by the k–ω model to approximate bed stress. Finally, this approximation is applied to the momentum equation in the SWE. Two experimental cases will be used to verify the SCM by comparing runup height, surface fluctuation, bed stress, and turbulent intensity values. The SCM shows good comparison to experimental data for all before-mentioned parameters. Further analysis shows that the wave Reynolds number increases as the wave propagates and that the turbulence behavior in the boundary layer gradually changes, such as the increase of turbulent intensity.

1. Introduction

The boundary layer approach in approximating bed stress under wave motion is crucial, especially in bed stress related analyses, i.e. sediment transport and scouring. It is highly important in relevance to coastal morphology changes. An extreme example of coastal morphology changes is given by the effect of a tsunami wave such as was shown in the recent Great East Japan Tsunami, 2011 and the Great Indian Ocean Tsunami, 2004. Studies on bed stress behaviors under wave runup may provide better understanding of this phenomenon with respect to future disaster.

The studies of tsunami effects on coastal regions are normally conducted by field assessment, modeling, or experiment. The solitary wave approach is commonly used in the study of tsunamis. One of the leading studies on solitary wave runup is given by Synolakis (1986, 1987) in which he conducted experiments and an analytical solution for runup height. The work has been used as a benchmark for other various models. The popularity of a modeling approach in wave runup study is continuously increasing. Current trends in wave runup modeling emphasize on travel time, runup height or inundated area. However, studies emphasizing on bed stress and boundary layer, especially under wave runup, are not common yet. Boundary layer beneath the wave motion is essential, especially in the coastal morphology changes. The sediment transport process under wave motion is closely related to the bed shear stress, which is influenced by the boundary layer beneath the wave itself (Vittori and Blondeaux, 2008).

There are very limited resources regarding boundary layer for solitary waves, especially in open-channel flumes. Measurement of turbulent behavior requires multiple wave cycles with the same initial conditions of still water level. It is considered to be difficult and time consuming to accomplish these conditions in open-channel flumes. Studies mainly use closed-channel flumes, which may resemble the solitary profile to some extent. Liu et al. (2007) have reported that the bed stress changes its sign in the deceleration phase to the opposite direction of the free stream velocity. Sumer et al. (2010) investigated and proposed Reynolds number criteria for a boundary layer under solitary waves. Tanaka et al. (2011) developed a new generation method for investigating the boundary layer under solitary waves. These studies have provided valuable information on the boundary layer under solitary wave motion. However, the boundary layer under wave runup has not been investigated widely since the closed-channel flumes experiment neglects the effect of nonlinearity. Recently, Sumer et al. (2011) conducted breaking solitary wave experiments in an open channel. Several measurements were performed, including the surface profile, the bed stress and its fluctuation. The experiment was conducted on a

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sloping beach with 1/14 slope with an incoming wave Reynolds number of 54,000. Based on criteria for solitary wave from Sumer et al. (2010), this condition falls in the laminar region. However, the criterion was derived from a closed flume experiment. In this experiment, it was found that the Reynolds number increases as the wave travels to the shore and may reach as high as 300,000 with significant turbulence observed.

Study on the boundary layer under solitary waves by Suntoyo and Tanaka (2009) has shown good accuracy of bed stress approximation from the boundary layer using a numerical model. Two equation models are often used to assess the boundary layer properties with k-ε and k–ω being the most common. The k–ω model has the ability to accommodate the roughness effect of the bed boundary condition, and is considered to be more accurate in assessing the boundary layer properties (Adityawan and Adityawan, 2011). Adityawan and Tanaka (in press) proposed the simultaneous coupling method (SCM) to assess boundary layer under non-breaking solitary wave runup. They developed the SCM that couples the SWE with the k–ω method. The basic idea is to obtain an efficient model such as the SWE yet capable of assessing the boundary layer beneath the wave itself. However, the wave Reynolds number in the experiment is very low; hence, there was no significant turbulence activity observed. Nevertheless, they have made it clear that bed stress assessment using the boundary layer approach provides information on known bed stress behaviors under wave motion (i.e. phase shift and sign change), which are not accessible when using the empirical Manning approach.

The modeling of breaking solitary wave runup has been widely studied through various different approaches. An accurate reproduction of breaking waves requires a 2D vertical system to simulate the dissipation such as given by NEWFLUME (Lin et al., 1999) and CADMAS SURF (Isobe et al., 1999). The breaking wave simulation in the SWE and other depth-averaged models are not able to accurately represent breaking waves. The Boussinesq model requires a breaking term to be included, which is determined by a calibration process with experimental or field data. Zelt (1991) conducted a detailed laboratory experiment and developed numerical models based on the Boussinesq type of model, accommodating the constant friction coefficient and artificial dissipation for breaking waves. However, it was found that the constant friction coefficient value was not a good solution and should be adjusted in time and space. The SWE based model, on the other hand, is relatively flexible to modify and to accommodate various treatments. Implementation of certain finite difference numerical schemes in the SWE enhances its capability in modeling the breaking waves. The Leapfrog scheme performs well in solving the SWE due to the nature of the scheme that provides diffusive effect (Imamura, 1995). Thus, it is widely used in far field tsunami simulations. Other finite difference numerical schemes, such as the Mac Cormack scheme, were used to investigate runup of a uniform bore on a sloping beach (Vincent et al., 2001). Conventional finite difference methods suffer from high oscillation under shock. Artificial dissipation, i.e. Hansen (1962), or changing to a more dissipative scheme is commonly used to reduce the high oscillation. Nevertheless, these steps must be taken with care. Implementation of a strong dissipation scheme may lead to unrealistic results, such as the rapid decay of the wave. Additionally, a weak dissipation scheme may lead to numerical errors when dealing with abrupt changes. Moreover, artificial dissipation may require determination based on a trial and error procedure. Application of the Mac Cormack finite difference in combination with artificial dissipation is given for the 2004 Tsunami, Banda Aceh (Kusuma et al., 2008), which requires further enhancement of the method.

Finite volume schemes may provide robust ways to handle shock in the SWE model. Li and Raichlen (2002) developed their model based on the SWE without friction and verified their simulation using experimental data from Synolakis (1986). The breaking wave in their model was treated using the Weighted Essentially Non-Oscillatory (WENO). WENO schemes achieve higher order approximation by a linear combination of lower order fluxes or reconstruction that provides a high order accuracy and non-oscillatory property near discontinuities. They concluded that the model is simple yet reasonably suited for estimating solitary wave runup height. Modification of the Godunov-type scheme leads to a second order accuracy in space such as Monotonic Upstream Scheme of Conservation Laws (MUSCL) scheme (Toro, 1996). Combining it with the First Order Centered Scheme (FORCE) (Toro, 2001) and Total Variation Diminished (TVD) Runge-Kutta (Mahdavi and Talebbeydokhti, 2009) further enhanced the method. Employment of such scheme efficiently enhances the SWE capability for breaking wave simulations.

In this study, the SCM is enhanced using the FORCE MUSCL shock-capturing scheme for breaking wave simulations. Two case studies of breaking solitary wave runup are used to verify the model. The boundary layer assessment is verified with the latest open channel experiment by Sumer et al. (2011). This case is currently the only study that provides detailed measurement on bed stress and turbulence under solitary wave runup. The runup height estimation is verified with the well-known canonical problems by Synolakis (1986). This case has been widely used as numerical model benchmark for solitary wave runup.

2. Methodology

2.1. Governing equations

The SWE consists of the continuity equation and the momentum equation as follows:

$$\frac{\partial h}{\partial t}+\frac{\partial (Uh)}{\partial x}=0 \tag{1}$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+g\frac{\partial (h+z_b)}{\partial x}+\frac{\tau_0}{\rho h}=0 \tag{2}$$

where h is the water depth, U is depth averaged velocity, t is time, g is gravity, z_b is the bed elevation, ρ is fluid density and τ_0 is the bed stress. The Manning equation is commonly used to assess bed stress.

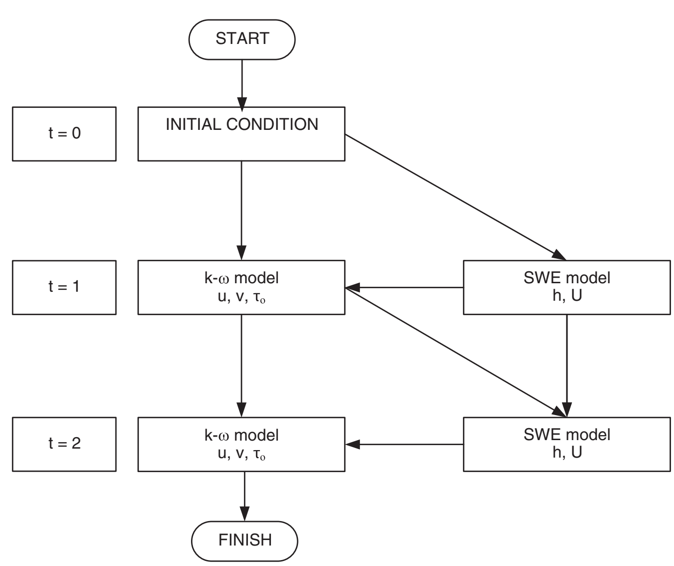

Fig. 1. Computation flow chart for SCM.