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Interaction of dispersive water waves with weakly sheared currents of arbitrary profile

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ABSTRACT

A set of depth-integrated equations describing combined wave–current flows is derived and validated. To account for the effect of turbulence induced by interactions between waves and currents with arbitrary horizontal vorticity, new additional stress terms are introduced. These stresses are functions of a parameter ***b*** that relates the relative importance of wave radiation stress and bottom friction stress to the wave–current interaction. To solve the equations, a fourth-order MUSCL-TVD scheme with an approximate Riemann solver is adopted. As a first-order check of the model, the Doppler shift effect and wave dispersion over linearly sheared currents are analytically shown to be retained appropriately in the equation set. The model results are then validated through comparisons with three experimental data sets. First, based on the experiments of Kemp and Simons (1982, 1983), a reasonable functional form of ***b*** is estimated. Second, simulations examining the propagation of a weakly dispersive wave over a depth-uniform or linearly sheared current are performed. Finally, the model is applied to a more complex configuration where bichromatic waves interact with spatially varying currents. Simulated results indicate that the model is capable of predicting nearshore interactions of waves with currents of arbitrary vertical structure. One of the unique properties of the developed model is its ability to assimilate an external current field from any source, be it from a circulation model or an observation, and predict the interaction of a nonlinear and dispersive wave field with that current.

1. Introduction

In combined wave and current environments, nonlinear interactions can play a significant role and we cannot simply superpose the two components. Nonlinear interactions have non-negligible impacts on the hydrodynamics of a wave–current system, especially in the turbulent boundary layer with high roughness (Davies et al., 1988; Grant and Madsen, 1979). Turbulent processes embedded in flow structures are of particular interest in a wave–current situation.

Turbulent interaction[1] of waves and current has been investigated quite extensively in the past few decades, both theoretically and experimentally. Thomas (1981, 1990), Kemp and Simons (1982, 1983), Klopman (1994), and Swan et al. (2001) conducted related laboratory experiments. Most recently, Fernando et al. (2011) presented a series of experimental results on wave–current interactions at an angle, along with comprehensive reviews on previous works. One interesting finding of these experiments is that when waves and currents are coflowing/following (or counterflowing/opposing), the mean velocity near the free surface tends to curl back (or forward), generating a negative (or positive) velocity gradient ($\partial u/\partial z$). A common explanation for this mixing-like process induced by waves is that the presence of waves introduces additional shear stress on the underlying current, yielding modified Reynolds stresses in the combined wave–current field (You, 1996; Groeneweg and Klopman, 1998; Huang and Mei, 2003; Umeyama, 2005; Yang et al. 2006; Lin, 2008). In this context, Umeyama (2005) conducted laboratory investigations to provide insight into the previously mentioned physics of waves and currents. He conducted a series of experiments on wave–current turbulence intensities and Reynolds stresses in combined wave–current flows. Experiments showed the modification of Reynolds stress (i.e., $\langle \overline{u'w'} \rangle$) by the action of waves on mean flows.

In the numerical regime, models for wave–current interactions have been developed for deep or finite-depth waves (Nwogu, 2009; Swan and James, 2001; Swan et al., 2001) and long waves (Benjamin, 1962; Freeman and Johnson, 1970; Shen, 2001). Grant and Madsen (1979) suggested different eddy viscosities for inside and outside the bottom boundary layer, and some works stem from this (Christoffersen and Jonsson, 1985; Davies et al., 1988). The majority of turbulent wave–current models were employed to examine extensively near-bed physics (Kim et al., 2001) rather than studying the entire water column. A few numerical models have shown the capability to recreate the aforementioned process of turbulence mixing throughout the column

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[1] Refers to nonlinear interaction involving turbulent processes in this study.

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depth, induced by waves or currents (Dingemans et al., 1996; Groeneweg and Klopman, 1998; Olabarieta et al., 2010). In addition, some equations have been proposed to describe the velocity profile of the mean flow either empirically (You, 1996) or analytically (Huang and Mei, 2003; Yang et al., 2006).

Despite efforts to understand these physics, there has been little development to account for vertically-dependent, wave–current effects in depth-integrated, dispersive models, which are increasingly used to predict nearshore hydrodynamics. In this study, we derived a set of depth-integrated equations describing combined wave–current flows. The effects of turbulence, introduced not only by bottom friction but also by nonlinear interactions between waves and underlying currents with arbitrary horizontal vorticity, are included. The outline of the paper is as follows. First, the physics of wave–current interactions are briefly reviewed, followed by their mathematical formulation. The next section is devoted to the description of the model developed, including a numerical scheme. The validity of the current model is assessed in Section 4. Results from three numerical simulations are presented and compared with experimental data to demonstrate the significance of the present model.

2. Brief review on wave–current interactions

2.1. Waves over current

Waves traveling over currents experience a modulation in their kinematics and dynamics, for example, a change in wave number, frequency, and wave height. Waves become steeper and higher on following currents, and vice-versa for opposing currents. Currents modify the wave frequency in such a way that the wave period will be longer over following currents and shorter over opposing currents, in a stationary reference frame. The Doppler shift is a common concept to explain such modulations in wave dispersion. For uniform background currents, this effect can be shown mathematically and expressed as follows:

$$\sigma^2 = (\omega - k u_C)^2 = gk \tanh kh \tag{1}$$

where σ is intrinsic (or relative) angular frequency, ω the apparent (or absolute) angular frequency, k the wavelength, u_C the current speed and h water depth. For linearly sheared current, σ is found to be (Jonsson et al., 1978; Nwogu, 2009),

$$\sigma^2 = \{gk - \mathcal{W}_0(\omega - k u_{Cs})\} \tanh kh \tag{2}$$

where u_{Cs} is current velocity at the free surface and $\mathcal{W}_0$ is the current's constant vorticity. Nwogu (2009) also presented a modified dispersion equation for arbitrarily sheared currents under finite amplitude waves. Another effect of currents on waves, which is worth mentioning here, is refraction due to current variation in space, which is similar to that caused by bathymetric changes (Lin, 2008).

2.2. Current under waves

Current fields also tend to be deformed by wave action. A wave riding on a current has many potential factors that may affect the mean flow field (e.g., a radiation stress or bottom friction enhancement). The mechanism by which the wave changes the current is yet unclear; however, it is believed that nonlinear wave–current interactions exert an additional shear stress on the mean flow, feeding horizontal vorticity to the interior flow. This stress is considered to be generated by the radiation stress of waves and mean flows (Lin, 2008). Experimental results consistently show that this stress is capable of tilting the current velocity forward or backward, depending on the relative wave–current direction; it is maximized near the free surface and decreases with depth. In other words, the near-bed velocity is not affected significantly by such stress, so it can be modeled using the general "log-law" profile (Fernando et al., 2011; Kemp and Simons, 1982).

Although the above effect is relatively concentrated in the upper portion of the fluid, it should be included in modeling for a complete description of the velocity profile. A few equations have been proposed to identify the resultant velocity profile of mean flow under combined wave–current action. You (1996), for instance, suggested a semi-empirical formula based on experiments:

$$\frac{u(z)}{u_*} = \frac{1}{\kappa} \log \frac{z+h}{\delta} + C \frac{h}{\kappa u_* |u_*|} \log \frac{-z}{h} \tag{3}$$

where $u(z)$ is the mean horizontal velocity profile, u_* is shear velocity, z is the vertical axis pointing upward from free surface, κ is the von Karman constant, h is water depth and δ is roughness height. Although the dimensional parameter C can be obtained using the empirical formula of You (1996), C does not take into consideration the properties of waves. The second term in Eq. (3) represents the higher-order correction component to the first term (i.e., log-law profile, which has its origin in the Prandtl's mixing length hypothesis) under the wave-free situation. Similar formulations can be found in the reports by Umeyama (2005) and Yang et al. (2006), with minor differences. Typically, bed roughness is enhanced by wave–current coexistence, and this effect can be realized theoretically by considering bottom friction for combined wave–current flows (see Grant and Madsen, 1986).

3. Boussinesq-type equations for combined waves and currents

In this section, a set of depth-integrated equations for long waves under current fields is derived. The perturbation approach to manipulate a primitive equation set into an approximate one is used in the present study. This technique is adopted to develop Boussinesq-type equations including the effects of wave–current interaction on the vertical structure of the flow. Viscous terms can be added as correction terms to the inviscid Boussinesq equations to explain bottom-induced turbulence effects (Kim et al., 2009). The primary technique to introduce turbulence induced by wave–current interactions use here is the same as that used by Kim et al. (2009). It is important to note that the approach developed in this section requires, as input, an external current field; this current field is not solved for directly in this theory. An application of this theory would be to understand the modification of the wave field and the wave-induced stresses due to tidal currents, where the tidal currents are estimated from a different (circulation) model or from observations, and are known a priori. A similar conceptual approach can be found in the work of Rego et al. (2001).

Fundamental to the perturbation approach used here is that the interaction between the wave and the current field in the small-time-scale (sub-wave period) is second-order, and that the velocity and Reynolds stresses can be divided into a current-only component (e.g. from some external model such as Delft3D) and a wave component which includes to first order the wave-only flow and to second order the interaction component of the wave and current. While these dynamics are occurring simultaneously and are interacting, it is the purpose of the perturbation approach to allow us some flexibility in de-coupling and simplifying the problem for certain parameter ranges. The calibrations and validations presented in Section 4 then become paramount in understating the practical accuracy and usability of the model.

3.1. Non-dimensionalized governing physics and boundary conditions

Physical variables are defined as shown in Fig. 1 to describe the propagation of waves over depth-varying currents. These variables are normalized, for the perturbation process, by the characteristic shallow-water variables introduced below. Typical length scales ℓ_0 and h_0 are used for horizontal and vertical coordinates, respectively.