Ocean Engineering 84 (2014) 213–227

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Mixing parameterization: Impacts on rip currents and wave set-up

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ARTICLE INFO

Article history:
Received 9 September 2013
Accepted 19 April 2014
Available online 9 May 2014

Keywords:
Bottom friction
Vertical mixing
Wave set-up
Nearshore processes

ABSTRACT

Wave set-up is often underestimated by the models (e.g. Raubenheimer et al., 2001). Our paper discusses how the wave set-up may be changed by the inclusion of turbulent mixing in the bottom shear stress. The parameterization developed in Mellor (2002) for phase-averaged oscillatory boundary layer is used for this purpose. Two studies are carried out. The dependence of the parameterization on the vertical discretization and on the magnitude of the near-bottom wave orbital velocity is investigated. The function that distributes the turbulent terms over the vertical is modified, giving a good agreement with the average of the phase-resolved velocities, but an overestimation of the turbulent phase-resolved velocities. Applying that parameterization to simulate laboratory conditions in the presence of rip currents gives accurate magnitudes of the rip velocity, particularly in a fully coupled wave–current configuration, with an RMS error of about 4%. Compared to a model using the more standard Soulsby (1995) parameterization, the wave set-up is increased by about 12% when using the alternative parameterization. Thus the bottom shear stress is sensitive to the mixing parameterization with a possible effect of turbulence on the wave set-up. Further measurement and parameterization efforts are necessary for practical applications.

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1. Introduction

Waves in the nearshore zone drive morphodynamic and hydrodynamic responses at many spatial and temporal scales (e.g. Svendsen, 2006). The most obvious hydrodynamic features are longshore currents (Bowen, 1969) and a mean sea level increase on the shore face (e.g. Longuet-Higgins and Stewart, 1963). Longuet-Higgins (1970) models the bottom shear stress as a linear combination of the alongshore current, the near-bottom orbital velocity and the bottom friction coefficient. As opposed to that, friction is believed to be a secondary term in the cross-shore momentum balance in which the wave-induced momentum flux divergence is mostly balanced by the hydrostatic pressure gradient associated with the wave set-up (e.g., Apotsos et al., 2007). An accurate parameterization of friction is thus the first priority when modeling flows in a surf zone. Many in situ experiments tried to determine a physical roughness parameter and various studies aimed at estimating meaningful friction coefficients from observed flow patterns (Feddersen et al., 2000, 2003). These studies suggest that friction may not only be a function of bottom roughness, but also depend on wave breaking. Other sources of discrepancy between roughness and friction coefficients may stem from differences in roughness between the alongshore and cross-shore directions, because of specific form drags over bedforms (e.g. Barrantes and Madsen, 2000), and from the multiple velocity time scales that must be accounted when investigating the effect of bottom friction on either of the flow components (e.g., the wave effects on the dissipation of infragravity waves as in Reniers et al., 2002).

Several studies (e.g. Raubenheimer et al., 2001; Apotsos et al., 2007) reported an underestimation by the models of the wave set-up, in particular in depths shallower than about one meter. So, our purpose here is to investigate a parameterization of wave breaking effects on bottom friction, which impacts the wave set-up, by adding breaking-induced turbulence to the phase-averaged mixing scheme proposed by Mellor (2002) (hereafter referred to as ML02) for modeling the bottom boundary layer. The parameterization uses turbulent kinetic energy to represent the influence of wave-induced near-bottom turbulence on the mean flow, and was shown to accurately reproduce the observed current profiles in the case of an oscillatory bottom boundary layer (Mellor, 2002). We

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http://dx.doi.org/10.1016/j.oceaneng.2014.04.021
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extend its use by assessing its performance in another modeling framework and focusing on its ability to reproduce nearshore hydrodynamics.

In Section 2, we redo the validation case presented in Mellor (2002) for a one-dimensional oscillatory flow superimposed to a mean flow, to validate our implementation of the ML02 parameterization. Tests in the presence of wave breaking are also performed. In Section 3, the mixing parameterization is evaluated for a nearshore situation with rip currents. The ML02 results are tested against the laboratory data of Haas and Svendsen (2002). A comparison with the Soulsby (1995) parameterization is also performed. Conclusions follow in Section 4.

2. Oscillatory bottom boundary layer

We investigate the effects of vertical mixing on the bottom shear stress with the mixing parameterization proposed by Mellor (2002). The same equations and forcing conditions as in the original paper of Mellor are used. Our experiment describes the oscillation of the bottom boundary layer with the wave phase for a *one-dimensional vertical case*. The mixing parameterization aims at reproducing the effects of these oscillations in phase-averaged models that do not solve explicitly the wave phase.

First, we compare phase-averaged simulations obtained with the mixing parameterization, with phase-resolving simulations, for a non-breaking case. Next, we study the behavior of the parameterization in the presence of wave breaking.

2.1. Methodology

We use the MARS hydrodynamical model (Lazure and Dumas, 2008), with some modifications to simulate a one-dimensional vertical case. In MARS, the pressure projection method is implemented to solve the unsteady Navier–Stokes equations under the Boussinesq and hydrostatic assumptions. The model uses the ADI (Alternate Direction Implicit) time scheme according to Bourchtein and Bourchtein (2006). Finite difference schemes are used for the spatial discretization, which is done on an Arakawa-C grid.

The equations of motion for a horizontally forced, one-dimensional vertical, incompressible, unsteady flow are

$$\frac{\partial u}{\partial t} = \frac{\tau_{0x}}{h} + \lambda u_{bx}\omega \cos(\omega t) + \frac{\partial \tau_x}{\partial z}, \tag{2.1}$$

$$\frac{\partial k}{\partial t} = \underbrace{\frac{1}{D^2}\cdot\frac{\partial}{\partial \varsigma}\left(\frac{\nu_V}{s_k}\cdot\frac{\partial k}{\partial \varsigma}\right)}_{=\text{Diff}} + \text{B} \underbrace{-\epsilon}_{=\text{Diss}} + \underbrace{\text{P}+\mathcal{P}_k}_{=\text{Prod}}, \tag{2.2}$$

$$\frac{\partial \epsilon}{\partial t} = \frac{1}{D^2}\cdot\frac{\partial}{\partial \varsigma}\left(\frac{\nu_V}{s_\epsilon}\cdot\frac{\partial \epsilon}{\partial \varsigma}\right) + \frac{\epsilon}{k}(c_1\ \text{Prod} + c_3\ \text{Buoy} - c_2\epsilon) + \mathcal{P}_\epsilon \tag{2.3}$$

where u is the flow velocity in the x-direction, k is the turbulent kinetic energy (hereafter TKE), ϵ is the turbulent dissipation, D is the mean depth and $h = D/2$, ς is the terrain-following coordinate and t is the time. The term τ_x is the x-component of the Reynolds stress. When we consider the phase-resolving solution, all quantities described in Eqs. (2.1)–(2.3) depend on the wave phase (with $\lambda = 1$ in Eq. (2.1)), the forcing terms depend on time and all phases are simulated. The wave phase is given by $\Phi = 360^\circ \times t/T$ (where T is the wave period set to 9.6 s as in Mellor's study). For phase-averaged simulations, all quantities described in Eqs. (2.1)–(2.3) are phase-averaged (with $\lambda = 0$ in Eq. (2.1)) and the forcing terms become time-independent.

Note that for the phase-resolving solution, the momentum equations in terrain-following coordinates with $\lambda = 1$ are the same as Eqs. (9a) and (9b) in Mellor (2002), except the use of a k-epsilon model to parameterize vertical mixing. Indeed, we use the model of Walstra et al. (2000) to include the dissipation due to wave breaking which is linearly distributed over a distance equal to $H_{rms}/2$. This model is based on a k-epsilon closure scheme and requires the additional terms $\mathcal{P}_{kb}$ and $\mathcal{P}_{\epsilon b}$ in Eqs. (2.4) and (2.5), respectively.

In Eqs. (2.2) and (2.3), c_1, c_2 and c_3 are constant parameters. The terms P and B are related to the production and dissipation of TKE by shear and buoyancy, respectively; the B term is set to zero in our case. The wave forcing is induced by the pressure gradient, $u_{bx}\omega \cos(\omega t)$, where u_{bx} is the x-component of the near-bottom wave orbital velocity and ω is the wave intrinsic radian frequency. The mean flow is generated by a force that acts similar to a barotropic pressure gradient τ_{0x}/h, where τ_{0x} is the x-component of the mean wall shear stress vector. Two source terms ($\mathcal{P}_k$ and $\mathcal{P}_\epsilon$) are added to the standard k-epsilon turbulent scheme to model the effects of both bottom friction and wave breaking:

$$\mathcal{P}_k = \underbrace{\alpha\frac{4D_w}{H_{rms}}\left(1-\frac{2z'}{H_{rms}}\right)_{z' \le z_{ref}}}_{=\mathcal{P}_{kb}} + \underbrace{\beta\omega|\mathbf{u}_b|^2(F_{1\psi}F_{2z})^3}_{=\mathcal{P}_{kf}}, \tag{2.4}$$

$$\mathcal{P}_\epsilon = \underbrace{1.44\left(\alpha\frac{\epsilon}{k}\right)\left[\left(\frac{4D_w}{H_{rms}}\left(1-\frac{2z'}{H_{rms}}\right)_{z' \le z_{ref}}\right)\right]}_{=\mathcal{P}_{\epsilon b}} + \underbrace{\beta\frac{\epsilon}{k}[C\omega|\mathbf{u}_b|^2(F_{1\psi}F_{2z})^3]}_{=\mathcal{P}_{\epsilon f}} \tag{2.5}$$

where $F_{1\Psi}$ and F_{2z} are given in Mellor (2002) (see his Eqs. (18), (20) and (21a)). $F_{1\Psi}$ accounts for the angle between the waves and the current. F_{2z} distributes the source terms over the water column and therefore depends on depth. F_{2z} is also a function of the bottom roughness (z_0). z_0 is set to 3.06×10^{-5} m to keep only the terms $0.0488 + 0.02917lz + 0.01703lz^2$ in F_{2z}. C is a non-dimensional constant equal to 0.9337. $|\mathbf{u}_b|$ is the magnitude of the orbital velocity such as $|\mathbf{u}_b| = (u_{bx}^2)^{1/2}$. z_{ref} is the distribution length for the dissipation due to wave breaking (D_w). The wave dissipation is computed with the help of the friction velocity ($u_\star$) such as $D_w = \alpha' u_\star^3$, with $\alpha' = 100$ (Craig and Banner, 1994). $u_\star$ is the water friction velocity. H_{rms} is the root mean square significant wave height. z' is the distance from the surface.

Four situations discussed are the following:

(a) phase-averaged solution without breaking wave ($\alpha = 0, \beta = 1$);
(b) phase-averaged solution with breaking wave ($\alpha = 1, \beta = 1$);
(c) phase-resolving solution without breaking wave ($\alpha = 0, \beta = 0$);
(d) phase-resolving solution with breaking wave ($\alpha = 1, \beta = 0$).

The coefficients α and β are chosen to combine the turbulent source terms introduced by Walstra et al. (2000) and Mellor (2002). The input of TKE resulting from wave breaking is distributed over the water column as in Rascle et al. (2013), who highlighted the efficiency of this modeling strategy, and not injected at the surface (e.g. Feddersen and Trowbridge, 2005; Burchard, 2001).

Aside from the previous equations, the formulation of the bottom shear stress must be modified to account for the wave effects. For the *phase-averaged solution*, the ML02 formulation uses near-bottom TKE such as

$$\tau_{bx} = \frac{u\kappa S_{M0}\sqrt{2k_0}}{\ln\left(\frac{z_b}{z_0}\right)}, \quad z_b > z_0, \tag{2.6}$$

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