Marine Pollution Bulletin xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Development and application of an oil spill model with wave–current interactions in coastal areas

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Oil spill
Wave–current interactions
Radiation stress
Unstructured mesh

ABSTRACT

The present paper focuses on developing a numerical oil spill model that incorporates the full three-dimensional wave–current interactions for a better representation of the spilled oil transport mechanics in complicated coastal environments. The incorporation of surface wave effects is not only imposing a traditional drag coefficient formulation at the free surface, but also the 3D momentum equations are adjusted to include the impact of the vertically dependent radiation stresses on the currents. Based on the current data from SELFE and wave data from SWAN, the oil spill model utilizes oil particle method to predict the trajectory of individual droplets and the oil concentration. Compared with the observations in Dalian New Port oil spill event, the developed model taking into account wave–current coupling administers to giving better conformity than the one without. The comparisons demonstrates that 3D radiation stress impacts the spill dynamics drastically near the sea surface and along the coastline, while having less impact in deeper water.

1. Introduction

The increasing demands for accurate forecast of oil transport trajectories have resulted in significant advancement of numerical models during the last two decades (ASCE, 1995). Oil spill models have evolved, from two-dimensional trajectory-type model to three-dimensional models including transport and weathering processes (Chao et al., 2003), from structured grid to unstructured grid (Cucco et al., 2012). Meanwhile, the linked ocean-wave hydrodynamic model research has made significant progress, so oil spill model improvements are required to keep pace with it. Once spilled into waters oil is immediately transported by the environmental conditions, including winds, currents and waves. Compared with the first two factors, the wave-induced component is the least investigated. This is largely due to the perception that wave-induced drift has a much smaller magnitude compared to direct wind shear and current-induced advection. The assumption could be invalid in some cases, especially in the wave-dominated regions. There is some evidence that for smaller scales surface waves can yield an equally important contribution to horizontal dispersion (Herterich and Hasselmann, 1982).

The hydrodynamic structure become complicated, given the interactions among winds, waves and currents and the generation of turbulent kinetic energy by shear and breaking wave activity. In some models, only the empirical relationship between vertical dispersion and breaking wave energy is considered, the horizontal currents induced by winds and waves are normally lumped together and represented by an empirically based drift factor and deflection angle dependent on the local wind speed (Al-Rabeh et al., 1989). A drawback of this method is the sea state at any water site comprises a combination of waves generated locally by the wind and waves propagating over large distances. The accurate prediction of water waves requires knowledge of both local conditions, to estimate the wind-sea, and more distant wave conditions and associated transformations to estimate the swell. Most waves will break in the surf zone where the flow patterns are dominated by wave shoaling and breaking, and wave-induced currents strongly influence oil slick transport process. Meanwhile, ambient tidal currents can strongly affect wave transformation, which create a Doppler shift and cause wave refraction, reflection, breaking, and wave generation by wind (WISE Group, 2007). The universal coexistence of waves and currents in the coastal waters makes

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http://dx.doi.org/10.1016/j.marpolbul.2014.05.009
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Please cite this article in press as: Guo, W., et al. Development and application of an oil spill model with wave–current interactions in coastal areas. Mar. Pollut. Bull. (2014), http://dx.doi.org/10.1016/j.marpolbul.2014.05.009

the coastal systems highly complex, so that the modeling of wave and current as well as their mutual interactions has special value for engineering applications, such as the resuspension and deposition of sediment and the transport of pollutants. The interplay problem is made quite difficult by the difference in time scales between gravity surface waves with periods of several seconds and currents (mainly tidal) with periods of several hours (Wolf and Prandle, 1999). Computational limitations have limited applications of phase-resolved equations, such as Boussinesq-type equations and Navier–Stokes equations, in environmental issues, while phase-averaged equations is more applicable for oil spill trajectory and fate modeling. Effects of waves on currents include the bottom friction coefficient, the effective surface drag coefficient for wind-driven currents, and radiation stress, first introduced by Longuet-Higgins and Stewart (1960, 1962), which has helped to explain such phenomenon as wave setup, surf beats, generation of alongshore currents in the surf zone resulted from wave–current interactions. Putrevu and Svendsen (1999) observed that the vertical nonuniformity of the horizontal velocities accounts for the order of magnitude enhancement of lateral mixing. Given the importance of mixing due to wave-induced currents, addition of a wave radiation stress term to the momentum equation to account for the effect of phase-averaged waves on currents has been used in a coupled wave–current modeling system (Xie et al., 2001). It should be pointed out that the conventional radiation stress defined in the vertically integrated form was unsuitable for adoption in the vertically dependent momentum equations. Therefore, a series of depth-dependent radiation stress formulations have been developed (Mellor, 2003, 2005, 2008, 2011; Xia et al., 2004), which has been employed in 3-D circulation models. Among these formulations, the one derived by Mellor (2008) gave the most accurate mean currents and turbulence pattern inside and outside the surf zone (Sheng and Liu, 2011). Through simulations of several cases, the similar opinion was concluded by Haas and Warner (2009). In the past few years various quasi-three-dimensional and three-dimensional wave–current coupled models have been developed (Putrevu and Svendsen, 1999; Kumar et al., 2011), but the application to oil spill transport is still limited.

In this study, we aim to develop a robust wave–current coupled hydrodynamic model, which can provide for accurate information for prediction of oil pollution disasters in coastal regions. In the following, the oil spill model framework is illustrated, which employs a third-generation wind wave model (SWAN) and a three-dimensional hydrodynamic model (SELFE), to incorporate wave–current interactions. The wave–current coupling validation is presented in Section 3. An application is devoted to evaluating effects of the coupled hydrodynamic system on oil spill trajectories by compared the numerical model with measured data in Section 4. Summaries and conclusions are given in Section 5.

2. Numerical oil spill model

The oil model simulates transport and weathering processes by means of a particle tracking method using the wave data from SWAN (Simulating WAves Nearshore) and the current data from SELFE (Semi-implicit Eulerian–Langrangian Finite-Element), where the feedback on each other are taken into account. The main oil processes determining the fate of oil includes: advection of oil particle by winds, currents and waves; mechanical spreading due to inertia, gravity, viscous and interfacial tension; turbulent diffusion; entrainment into water body by breaking waves; evaporation of floating oil; emulsification; dissolution; sticking of oil to the coastline. Changes of oil properties (density, viscosity, water content) caused by the aforementioned processes are also included. The processes are schematically outlined in Fig. 1.

2.1. Wave–current coupling module

2.1.1. Wave model

The wave module based on wave spectral numerical model is adopted to offer wave conditions with enough resolution and accuracy. SWAN (Booij et al., 1999) is a well-known numerical wave model for computing random, short-crested waves in coastal areas, for its ability to take into account of the shallow water effects of triad wave-wave interactions and depth-induced wave breakings. In SWAN, the evolution of wave spectrum is described by the action balance equation rather than the energy transport equation, because the wave action density spectrum is conserved in the presence of currents. An unstructured-grid procedure for SWAN has been developed to provide much better representation of complex boundaries such as coastlines and areas around islands than do conventional regular grids and the opportunity to concentrate mesh resolution in areas of interest (Zijlema, 2010). The evolution of the action density N is governed by the action balance equation, which is expressed as:

$$\frac{\partial N}{\partial t}+\frac{\partial(c_{gx}+u)N}{\partial x}+\frac{\partial(c_{gy}+v)N}{\partial y}+\frac{\partial c_\sigma N}{\partial \sigma}+\frac{\partial c_\theta N}{\partial \theta}=\frac{S_t}{\sigma} \tag{1}$$

where c_{gx} and c_{gy} are the wave group velocity in the x and y directions, u and v are the ambient horizontal current velocity, σ is the relative frequency, and θ is the wave direction. The quantities c_σ and c_θ are the propagation velocities in spectral space (σ, θ). The term S_t on the right-hand side is a source/sink of wind-wave generation, wave breaking, bottom dissipation, and nonlinear wave-wave interactions. Specific formulations for source/sink term are described in Booij et al. (1999).

2.1.2. Current model

The current module is based on the SELFE (A semi-implicit Eulerian–Lagrangian finite-element model) system. SELFE solves the 3D primitive equations, with hydrostatic and Boussinesq approximations. In a Cartesian frame, the continuity equation can be written as (Zhang and Baptista, 2008):

$$\nabla\cdot\mathbf{u}+\frac{\partial w}{\partial z}=0 \tag{2}$$

The 3D Reynolds momentum equations are:

$$\frac{\partial \eta}{\partial t}+\nabla\cdot\int_{-h}^{\eta}\mathbf{u}dz=0 \tag{3}$$

$$\frac{D\mathbf{u}}{Dt}+\nabla\cdot\int_{-h}^{\eta}\mathbf{u}dz=-f\mathbf{k}\times\mathbf{u}-\frac{1}{\rho_0}\nabla p_A-\frac{g}{\rho_0}\int_{z}^{\eta}\nabla\rho d\zeta+\nabla\cdot(\mu\nabla\mathbf{u})-g\nabla\eta+\frac{\partial}{\partial z}\left(\nu\frac{\partial\mathbf{u}}{\partial z}\right) \tag{4}$$

where $\mathbf{u} = (u, v)$ is the horizontal velocity, w is the vertical velocity, η is the surface elevation, h is the still water depth, $\nabla=(\partial/\partial x,\partial/\partial y)$ is the horizontal gradient operator, g is the gravitational acceleration, k is a unit vector of the z-axis (pointing vertically upward), f is the Coriolis factor, ν and μ are the vertical and horizontal eddy viscosities respectively solved from turbulence closure schemes, ρ_0 is a reference water density, and p_A is the atmospheric pressure. For the computation of the vertical diffusivities and viscosities, a Mellor–Yamada Level 2.5 turbulence closure scheme is adopted

This model is based on finite-element method and is run on unstructured horizontal grids with a hybrid vertical coordinates. SELFE has been widely used for coastal hydrodynamics simulations and marine environment forecasts (Liu et al., 2008; Roland et al., 2012).

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