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A phase-resolving, coupled-mode model for wave-current-seabed interaction over steep 3D bottom topography. Parallel architecture implementation

Konstandinos A. Belibassakis[(1)], *Theodoros P. Gerostathis and Gerassimos A. Athanassoulis*[(2)]

(1) Technological Educational Institute of Athens
(2) School of Naval Architecture and Marine Engineering, National Technical University of Athens.
Athens, GREECE

ABSTRACT

A phase-resolving, coupled-mode model is developed for the wave-current-seabed interaction problem, with application to wave scattering by steady currents over steep three-dimensional bottom topography. The vertical distribution of the wave potential is represented by a series of local vertical modes containing the propagating mode and all evanescent modes, plus an additional term accounting for the bottom boundary condition when the bottom slope is not negligible. Using the above representation, in conjunction with a variational principle, the problem is reduced to a coupled system of differential equations on the horizontal plane. If only the propagating mode is retained in the vertical expansion of the wave potential, and after additional simplifications, the above coupled-mode system is reduced to the mild-slope model derived by Kirby (1984) with application to the problem of wave-current interaction over slowly varying topography. The present system is discretized by using a second-order finite difference scheme and numerically solved by means of a parallel implementation, developed using the message passing programming paradigm on a commodity computer cluster. Thus, direct numerical solution is made feasible for realistic domains corresponding to areas with size of the order of several kilometers. The analytical structure of the present model facilitates its extension to treat non-linear waves, and it can be further elaborated to study wave propagation over random bottom topography and currents.

KEY WORDS: water waves, non-homogeneous currents, variable bathymetry, modified mild slope, couple-mode theory

INTRODUCTION

The prediction of wave propagation in nearshore and coastal areas is critical to engineering applications associated with coastal management and harbour maintenance. In regions where ambient tidal and other currents are strong, their effect on wave transformation can be substantial. They create a Doppler shift and cause wave refraction, reflection, and breaking, which can completely change the wave energy pattern. In particular, the characteristics of surface gravity waves present significant variations as they propagate through non-homogeneous currents, in the presence of depth inhomogeneities in variable bathymetry regions. For example, large amplitude waves can be produced when obliquely propagating waves interact with opposing currents, see, e.g., Mei (1983, Ch.3.7). This situation could be further enhanced by inshore effects due to sloping seabeds, and has been reported to be connected with the appearance of “giant waves”; see, e.g., Lavrenov & Porubov (2006). Extensive reviews on the subject of wave-current interaction in the nearshore region have been presented by Peregrine (1976), Jonsson (1990) and Thomas & Klopman (1997).

The study of spatial evolution of water waves and the investigation of scattering of realistic wave spectra over irregular currents, with characteristic length of variation comparable to the dominant wavelength, including the effects of bottom irregularities, can be supported by theoretical models treating the simpler problem of monochromatic waves interacting with steady inhomogeneous currents. Wave-current interaction models over slowly varying bottom topography have been developed and studied by various authors. Under the assumption of irrotational wave motion, Kirby (1984) derived a phase-resolving one-equation model, generalizing the mild-slope equation by Berkhoff (1972) in regions with slowly varying depth and ambient currents; see also Liu (1990). The latter model in its elliptic time-harmonic form has been exploited, in conjunction with numerical (finite-element, finite difference etc) solvers, to numerous wave-current-seabed interaction applications; see, e.g., Chen *et al* (2005) and the references cited there.

On the other hand, if the wave flow is assumed to be weakly rotational, as happens to be the case when waves are scattered by shearing currents characterised by stronger horizontal gradients, McKee (1987) derived another one-equation model, called the mild-shear equation. Still however, the validity of the mild-shear equation is based on the assumption of slow current and depth variations compared to the typical wavelength. In the case of flat bottom, the mild-shear model has been further enhanced by McKee (1996) by including an extra term and obtaining the so called enhanced mild-shear equation. The latter model is applicable to cases where the shearing current is varying on the scale of the wavelength. In the above works by McKee (1987, 1996) the current is considered to be flowing along one horizontal direction while the bottom topography varies in the other horizontal direction. Thus, the mild-shear model is more appropriate for problems of wave scattering by slowly varying depth and longshore-type ambient shearing currents.

In both the above approaches (mild-slope model, mild-shear model) the effects of evanescent modes, describing higher-order localised effects