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A coupled-mode technique for the prediction of wave-induced set-up in variable bathymetry domains and groundwater circulation in permeable beaches

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ABSTRACT

In the present work a complete phase-resolving wave model is coupled with an iterative solver of the mean-flow equations, permitting an accurate calculation of wave-induced set-up in intermediate and shallow water environments with possibly steep bathymetric variations. The wave model is based on the consistent coupled-mode system for the propagation of water waves in variable bathymetry regions, developed by Athanassoulis & Belibassakis (1999) and extended to 3D by Belibassakis et al (2001). This model improves the predictions of the mild-slope equation(s), permitting accurate treatment of wave propagation in regions with steep bottom slope and/or large curvature. In addition, it supports the correct calculation of wave velocity up to the bottom boundary. The coupled-mode model has been further extended to include the effects of energy dissipation from bottom friction and wave breaking, which are important for the accurate calculation of radiation stresses on decreasing depth. Furthermore, it has been used in conjunction with the mean flow equations to predict wave-induced set up and flow in closed and open domains. Finally, the resulting phase-averaged mean-pressure has been applied to calculate the induced groundwater circulation on a permeable beach, in the set-up region. Under the assumption that the groundwater flow is in the Darcy law regime, in the case of a stationary mean flow, the porous flow velocity can be obtained in terms of the pressure gradient. In this case, Massel (2001), the problem concerning groundwater circulation is governed by the Laplace's equation on the pressure, forced by Dirichlet data specified by the excess pressure on the sea bottom that is induced by the mean flow.

KEY WORDS: coupled-modes, mean flow equations, porous flow

INTRODUCTION

Wave transformation on beaches along with other important factors, such as wave breaking, set-up and run-up, play a significant role in the water table formation and groundwater flow, and contributes to the dynamics of the coastal zone. Useful information concerning all the above effects can be obtained from the solution of the slow-scale, mean-flow equations, forced by radiation stresses as well as the free-surface and the bottom stresses. The radiation stresses can be effectively calculated from the fast-scale wave flow properties; see, e.g., Mei (1983), Dingemans (1997).

As concerns the interaction of free-surface gravity waves with variable bottom topography, in water of intermediate depth and in shallow water, a broad class of approximation techniques has been developed, Dingemans (1997). Although the non-linear effects become significant as the shoreline is approached, a consistent linear solution is still very useful, providing a great deal of information concerning the wave field and its impact on the nearshore environment; see, e.g., Massel (1989). In addition, linear theory serves as the starting point for weakly nonlinear models, permitting the calculation of wave energy dissipation due to bottom friction and wave breaking by an indirect process, Dingemanns (1997), Massel & Brinkman (2001).

One very attractive family of models in variable bathymetry is obtained by reformulating the wave propagation problem as a system of equations on the horizontal plane with variable coefficients. Berkoff (1972) derived an one-equation model for gentle bottom slopes, called the *mild-slope equation*, in which the vertical distribution of the wave potential has been prescribed. Other derivations of similar or improved one-equation models, using either averaging techniques or variational principles, have been given by various authors; see e.g. the general survey by Porter & Chamberlain (1997). The basic restriction inherent to any one-equation model is that the vertical structure of the wave field is given by a specific, preselected function. In order to better describe the wave field when the bottom topography is not slowly varying and the depth is sufficiently small so that the wave strongly interacts with the bottom, Massel (1993) and Porter & Staziker (1995) derived *extended mild-slope models*, in which the vertical profile of the wave potential at any horizontal position is represented by a local-mode series involving the propagating and the evanescent modes. However, this expansion has been found to be inconsistent with the Neumann boundary condition on a sloping bottom, since each of the vertical modes involved in the local-mode series violates it and, thus, the solution, being a linear superposition of modes, behaves the same. This fact has two important consequences. First, the velocity field in the vicinity of the bottom is poorly represented and, secondly, wave energy is not generally conserved. This problem has been remedied by the *consistent coupled-mode model* developed by Athanassoulis & Belibassakis (1999).