Available online at www.sciencedirect.com
SCIENCE DIRECT®
Coastal Engineering 53 (2006) 419–439
Coastal Engineering
An International Journal for Coastal, Harbour and Offshore Engineers
www.elsevier.com/locate/coastaleng

Boussinesq modelling of transient rip currents

D. Johnson *, C. Pattiaratchi

Centre for Water Research, University of Western Australia, 35 Stirling Highway, Crawley, WA 6011, Australia

Received 10 January 2005; received in revised form 24 August 2005; accepted 24 November 2005
Available online 25 January 2006

Abstract

The flow on a plane beach with a random, directionally spread wave field was simulated with a Boussinesq model. The random wave spectra were directionally symmetric with their central direction perpendicular to the beach, so no constant longshore current was generated. Variable wave-averaged currents were generated because of the spatially variable wave field, and sometimes formed offshore directed rip currents that appear in variable longshore locations. The rip currents are associated with a vortex pair which is generated within the surfzone and subsequently propagates offshore. Analysis of the vorticity balance show that the main vorticity input occurs within the inner surfzone. Three different beach slopes and four different wave spectra are simulated. The frequency, duration, and intensity of the transient rips depend on both the beach slope and the incident wave spectra. The results have important engineering implications for the transport of material in the nearshore zone, in particular on longshore uniform beaches.

Keywords: Modelling; Boussinesq model; Surfzone; Rip currents

1. Introduction

Transient rips are narrow offshore flows generated in the surfzone. Unlike rip currents which are associated with a topographic rip channel, transient rips are spatially and temporally variable, and are temporary features which develop, have a specific lifetime and then decay. Importantly, they are not restricted to well-defined topographic variation and can occur on long shore uniform beaches.

Rip currents are generated by longshore inhomogeneities in the momentum flux gradient of the incident wave field, which can be caused by differential wave transformation over variable topography, as occurs over a rip channel in a longshore bar. However, the nearshore wave field can possess longshore variations in the onshore momentum flux on a plane, featureless beach, caused by

(1) Interaction of the incident wave field and the wave-averaged mean current (Dalrymple and Lozano, 1978; LeBlond and Tang, 1974).
(2) Interaction of the incident wave field with lower frequency waves such as edge waves (Bowen, 1969; Sasaki and Horikawa, 1978; Symonds and Ranasinghe, 2001).
(3) The inherent spatial variability of the incident wave field (Dalrymple, 1975; Tang and Dalrymple, 1989; Peregrine, 1998).

Transient rips of the second (Bowen and Inman, 1969) and third (Dalrymple, 1975; Fowler and Dalrymple, 1991; Hammack et al., 1991) types have been generated in the laboratory. There have been few measurements of transient rips in the field; Tang and Dalrymple (1989) made measurements of nearshore circulation, including (transient) rips, which were spatially and temporally variable and concluded that they were largely driven by the variability of the incident wave field. Johnson and Pattiaratchi (2004) (hereafter JP04) recently made Lagrangian measurements of transient rips where the swell was perpendicularly incident on a beach without an offshore bar or significant longshore variation. The trajectories showed narrow (length scales 20–30 m) offshore directed flows with typical flow speeds 0.2–0.5 ms^{-1} occurring at variable locations. The Lagrangian velocities showed that forcing occurs mainly at the start of the

* Corresponding author. Present address: MetOcean Solutions Limited, Suite 3, 17 Nobs Line, New Plymouth, New Zealand.
E-mail address: d.johnson@metocean.co.nz (D. Johnson).

0378-3839/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.coastaleng.2005.11.005

rip neck and that the neck subsequently spreads into a head region outside the surfzone. Eulerian measurements from the same experiment strongly supported the assertion that the rips did not persist at one location.

The usual definition of the nearshore current is the net flow after averaging over the incident short wave motion. Vertical averaging then defines a wave and depth-averaged current vector, $\bar{\boldsymbol{U}}$ which is governed by:

$$\frac{\partial \eta}{\partial t} + \nabla \cdot [(\bar{\eta} + h)\bar{\boldsymbol{U}}] = 0 \quad (1)$$

$$\frac{\partial \bar{\boldsymbol{U}}}{\partial t} + (\bar{\boldsymbol{U}} \cdot \nabla)\bar{\boldsymbol{U}} = -g\nabla\bar{\eta} + \mathbf{S} + \mathbf{L} + \mathbf{B} \quad (2)$$

where h is the still water depth, $\bar{\eta}$ is the wave-averaged surface elevation, $\mathbf{S}$ is short wave forcing, $\mathbf{L}$ is a term to describe lateral mixing, and $\mathbf{B}$ is bottom friction. Eqs. (1) and (2) are a set of forced shallow water equations, and with various simplifications are the theoretical basis for most descriptions of nearshore flow at frequencies below that of the incident waves.

To date most wave-averaged models solving Eqs. (1) and (2) have used wave drivers including shoaling, refraction, diffraction and wave-current interaction, but usually assume a homogeneous incoming wave field. As a result, the spatial variation of incident wave forcing is due to either variable mean water depth or interaction with the current. If there is feedback between the mean current/elevation field and the determination of the wave forcing, the first two transient rip generation mechanisms on a plane beach can be represented. Progress on more realistic wave-drivers (e.g. Kennedy and Kirby, 2003; van Dongeren et al., 2003) allows the spatial and temporal variation in the incident wave field to be modelled as well, thus potentially including the third rip generation mechanism even on longshore uniform bathymetry. Recent work by Reniers et al. (2004) shows the development of circulation cells on a longshore uniform beach when a spatially variable wave field forcing is used.

An alternative modelling approach used in this work is to actually resolve the incident wave field. Boussinesq-type equations (for a recent review, see Madsen and Schaffer, 1998) allow accurate simulation of surface waves from intermediate depth to shallow water. Simulation of a random wave field is possible, thereby implicitly including a spatially and temporally variable forcing of the wave-averaged currents. Furthermore, it also includes generation of vertical vorticity due to discontinuities in individual wave crests, something Peregrine (1998) has proposed as an important source of surfzone vorticity. Despite their potential for simulating complex hydrodynamics associated with random wave fields, they have received relatively little use for nearshore process research on open beaches; exceptions are Chen et al. (2003) and Kirby and Chen (2003) who simulated longshore currents at field scale.

This article reports the results of a modelling investigation of transient rip currents using a Boussinesq model. The model is first described, and details of its implementation for simulating four different idealised random wave fields on plane beaches, with slopes of 0.05, 0.03 and 0.015, are presented. A qualitative validation of the model is provided by showing that transient rips, consistent with field measurements, are generated. The results of the modelling experiments are presented with three primary aims:

- To demonstrate that a Boussinesq simulation of a fully random wave field with mean direction perpendicular to a plane beach generates spatially variable wave-averaged currents, including well-defined transient rip currents.
- To investigate the forcing mechanism and vorticity balance for transient rip currents.
- To quantify the effect of varying wave fields and beach slopes on transient rip activity.

2. Model implementation

The numerical modelling was carried out using a modified version of *Funwave*, an open source distribution of a model developed at *The Center for Applied Coastal Research, University of Delaware*. *Funwave* is based on the fully non-linear Boussinesq equations of Wei et al. (1995), with an additional term to include vertical vorticity conservation at second order in the dispersive parameter as described by Chen et al. (2003). For completeness and for the context of the subgrid parameters detailed later, an outline of the model follows, including the governing equations, treatment of wave breaking, subgrid mixing and boundary conditions. Detailed description of the model subgrid schemes can be found in Kirby et al. (1998a), Kennedy et al. (2000) and Chen et al. (2000).

The equation for the conservation of mass is:

$$\beta\eta_t + \nabla \cdot M + F_s = 0 \quad (3)$$

$$M = \Lambda\left[\mathbf{u} + \left(\frac{z_r^2}{2} - \frac{1}{6}(h^2 - h\eta + \eta^2)\right)\nabla(\nabla \cdot \mathbf{u}) + \left(z_r + \frac{1}{2}(h-\eta)\right)\nabla(\nabla \cdot (h\mathbf{u}))\right] \quad (4)$$

where $\mathbf{u}=(u,v)$ is the horizontal velocity vector at a reference depth of $z_r=-0.531h$. Subscript t denotes time differentiation. The still water depth is h, and η is the instantaneous surface elevation. The parameters β and Λ account for the presence of slots, which simulate the presence of the beach face, in the vicinity of the shoreline. The term F_s is a source function which operates along a strip in the seaward region of the domain; this effectively adds and subtracts mass from this strip, thereby generating waves.

The momentum equation is:

$$\mathbf{u}_t + (\mathbf{u} \cdot \nabla)\mathbf{u} + g\nabla\eta + V_1 + V_2 + V_3 - F_{br} - F_m + F_b = 0 \quad (5)$$