Coastal Engineering 60 (2012) 95–108

Contents lists available at SciVerse ScienceDirect

Coastal Engineering

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

Numerical experiments on interactions between wave motion and variable-density coastal aquifers

R. Bakhtyar *, D.A. Barry, A. Brovelli

Laboratoire de technologie écologique, Institut d'ingénierie de l'environnement, Faculté de l'environnement naturel, architectural et construit (ENAC), Station 2, Ecole polytechnique fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland

ARTICLE INFO

Article history:
Received 26 February 2011
Received in revised form 26 August 2011
Accepted 1 September 2011
Available online 2 October 2011

Keywords:
Beach profile changes
Groundwater exchange
Intermediate beach
Dissipative beach
Saltwater wedge
Variable-density flow

ABSTRACT

A comprehensive two-dimensional (cross-shore) process-based numerical model of nearshore hydrodynamics (based on the Navier–Stokes equations, k–ε turbulence closure and the Volume-Of-Fluid method), beach morphology, and variable-density groundwater flow (SEAWAT-2000) was developed. This model, which was applied at the field scale, relaxes simplifications in existing models that do not include such detailed mechanistic descriptions. Numerical experiments were conducted to investigate the effects of varying aquifer, beach and wave characteristics (e.g., inland groundwater head, sand grain size, different wave heights and periods) on the coupled system. Spilling and plunging breakers on dissipative and intermediate beaches were simulated. For a given set of boundary conditions, the model was run for 1 y without the hydrodynamic sub-model to achieve a realistic salt-/freshwater interface. Then, the hydrodynamic component was run for 15 min and the model results analyzed. The main features considered were groundwater circulation, saltwater wedge position, in/exfiltration across the beach face, and beach morphology. The predictions of the numerical model agree well with existing understanding and experimental measurements. For an inland watertable that is lower than the still water level (SWL), such that the groundwater flow is mainly landward, on both coarse and fine sand beaches the addition of wave motion moves the saltwater wedge further landward. For an inland watertable that is higher than the SWL, the opposite behavior occurred. The numerical experiments showed that more sediment transport takes place on intermediate beaches than on dissipative beaches. In addition, beach profile variations are greater under plunging breakers, while coarse sand beaches are steeper than fine sand beaches for the same wave conditions. There is a strong correlation between in/exfiltration and beach face deposition/erosion for the coarse beaches, while in/exfiltration has a slight effect on sediment transport for fine beaches. The model is capable of simulating the short-term evolution of foreshore profile changes, and beach watertable and saltwater wedge movement due to interactions between wave motion and coastal groundwater.

Nomenclature

Variable	*Description*	*Dimensions*
d	Local still water depth	L
D_{50}	50th percentile of the sediment diameter distribution	L
$\vec{g}$	Gravitational acceleration	LT^{-2}
H	Water wave height	L
H_b	Wave-breaking height	L
L	Wave length	L
t	Time	T
T	Wave period	T
Greek		
β	Local beach slope	LL^{-1}
ρ	Fluid density	ML^{-3}
ζ	Surf similarity parameter	–
ξ	Surf scaling parameter	–

1. Introduction

Most previous investigations concerned with modeling of interactions between ocean water and coastal groundwater focused on tide-induced watertable fluctuations, neglecting high-frequency wave-induced oscillations and variable-density groundwater flow (e.g., Brovelli et al., 2007; Li et al., 2001, 2007; Robinson et al., 2007b, 2009; Slooten et al., 2010; Teo et al., 2003; Xin et al., 2010). However, given the interplay of mechanisms inherent in coastal processes — mixing of fresh- and seawater driven by waves, sediment transport and beach profile changes — it is not possible to extrapolate readily existing results to realistic coastal zone behavior.

Abbreviations: ADE, Advection–Dispersion Equation; GWT, Groundwater table; NS, Navier–Stokes; RANS, Reynolds-Averaged Navier–Stokes; SWL, Still Water Level; TKE, Turbulent Kinetic Energy; TVD, Third-order Variational Diminishing; VOF, Volume-Of-Fluid.

* Corresponding author. Tel.: +41 21 693 8087; fax: +41 21 693 8035.
E-mail addresses: roham.bakhtyar@epfl.ch (R. Bakhtyar), andrew.barry@epfl.ch (D.A. Barry), alessandro.brovelli@epfl.ch (A. Brovelli).

0378-3839/$ – see front matter
doi:10.1016/j.coastaleng.2011.09.001

Waves in the nearshore zone are an important forcing on sediments and groundwater behavior. While waves induce instantaneous pore water flows below the beach face in response to individual bores and wave runup, these high-frequency flows are rapidly attenuated (Horn, 2006). As waves break, the resulting energy dissipation and changes in the onshore component of the radiation stresses induce an onshore upward tilt in the mean sea level. This creates (phase-averaged) hydraulic gradients on the beach surface, which result in seawater infiltrating the upper part of the beach and exiting the beach groundwater system near the wave-breaking point (Li et al., 2004; Mao et al., 2006; Xin et al., 2010). The two-dimensional numerical simulations of Li and Barry (2000) showed that this circulation was affected by the beach groundwater table elevation relative to the Still Water Level (SWL). However, these studies, like numerous other studies on coastal aquifer behavior (e.g., Barry et al., 1996; Jeng et al., 2002, 2005a,b; Li et al., 1999, 2000a,b, 2001, 2002b; Parlange et al., 1984), ignored density variations of pore water and associated density-dependent flows in the beach aquifer. The extent of seawater intrusion into fresh groundwater depends on the sea level, the tidal range of coastal waters, wave cycle, the groundwater recharge rate, and the porosity and sediment composition of the intertidal area. In the nearshore zone with highly dynamic oceanic forcing, mixing zones may form a salty layer above the fresh aquifer water due to wave runup (Barry and Parlange, 2004; Li et al., 2004). Advanced and comprehensive process-based numerical models are required to address directly the interacting processes involved.

One major mechanism for transport and circulation of coastal contamination in beach areas is high and low frequency seabed water pressure oscillations in the surf and swash zones that produce infiltration and exfiltration across the seabed (Bakhtyar et al., 2009a). In/exfiltration can impact on surf and swash zone processes such as nearshore hydrodynamics, momentum exchange and sediment transport. In/exfiltration across the beach face is not well understood, and so there is a need for further investigation into the details of this type of flow and its effects on beach morphology (Horn et al., 2007). Most previous numerical investigations focused on wave motion on impermeable beds and neglected the effect of in/exfiltration. However, a mechanistic understanding of the nearshore environment needs to account for interactions of seawater and beach groundwater (Horn, 2006), in particular the role of oceanic motion on sediment transport, foreshore profile changes and salinity distribution.

Numerous researchers have carried out theoretical calculations and field and laboratory experiments to study the interaction of ocean, coastal groundwater, sediment and salt transport (Bakhtyar et al., 2011; Lee et al., 2007; Li et al., 2002a). Three different approaches have been used to compute these processes driven by oceanic forcing (Robinson et al., 2009): (i) field experiments; (ii) laboratory measurements; and (iii) numerical simulations. Austin and Masselink (2006a,b) studied hydrodynamics, morphological change and sediment transport on a gravel beach, and concluded that infiltration has important consequences for morphological changes. Lee et al. (2007) studied experimentally the effects of groundwater level on the profile changes in a gravel beach and showed that berm moves up the beach as the groundwater level decreases. Sediment deposition is usually enhanced when the level of the beach watertable is lower than the SWL, while a higher groundwater level increases beach erosion, as has been shown in laboratory experiments (Bakhtyar et al., 2011; Li et al., 2002a). In/exfiltration affects nearshore zone sediment transport due to effective weight modification and boundary layer thickening or thinning (Turner and Masselink, 1998). Ataie-Ashtiani et al. (1999) developed a numerical model to study the effects of tidal fluctuations on groundwater, including the presence of a seepage face and the unsaturated zone. They showed that the effect of beach slope is important for predicting the watertable elevation. Recent field observations from exposed coasts have shown that wave forcing can also have a non-negligible impact on aquifer circulation (Cartwright et al., 2004), which in turn may affect sediment transport and beach profile changes. Additional discussion of the mathematical modeling approaches that have been used to simulate beach aquifers and their interaction with nearshore motion were summarized by Horn (2006) and Bakhtyar et al. (2009a).

Most numerical models that have been used to compute wave motions with a permeable bed are based on the Boussinesq and the nonlinear shallow water equations (Hoque and Asano, 2007; Karambas, 2006; Li et al., 2002a; Masselink and Li, 2001). Bakhtyar et al. (2011) have shown that more realistic Reynolds-Averaged Navier–Stokes (RANS) equations can be used instead. Moreover, the sediment transport models that have been used in previous studies have a certain validity range. Existing models do not resolve all potentially important details of groundwater flow and sediment transport, such as wave asymmetry effects, percolation, different wave characteristics and beach profile changes. Bakhtyar et al. (2011) developed a two-dimensional (cross-shore) process-based model for simulating wave motion on a permeable beach taking into account wave-aquifer interactions to investigate the effects of an unconfined coastal aquifer on beach profile evolution, and wave shoaling on the watertable. They computed nearshore hydrodynamic behavior using the RANS equations in conjunction with a k–ε closure turbulence model and the Volume-Of-Fluid (VOF) technique. Bed morphological changes were calculated using an empirical sediment transport formula that accounts for the influence of fluxes across the beach face. Aquifer hydrodynamics and the interactions between the fresh groundwater and the coastal waves were modeled using a groundwater flow model, although density dependence was not considered.

The aim of this work is to extend further the capabilities of the model presented by Bakhtyar et al. (2011) to include density-dependent groundwater flow. The model is used to evaluate the importance of hydrodynamic parameters — including wave height, wave period and porous media characteristics — on beach face morphology and beach aquifer dynamics (both fresh and seawater) in a field-scale setup. The model has not been validated against experimental data since no suitable data sets are available currently. On the other hand, the predictive capabilities of the each sub-module have been tested: The variable-density groundwater flow model and the setup used to represent the cross-shore section of the aquifer were validated using experimental data collected at the field- and laboratory scales, see for example Brovelli et al. (2007) and Robinson et al. (2007a, 2009). Validation of the nearshore hydrodynamic and sediment transport module can be found in Bakhtyar et al. (2009b). Finally, the coupled model was validated using a detailed set of experimental data collected in a wave simulator, and the comparison reported by Bakhtyar et al. (2011). Good agreement was found considering different conditions, in particular watertable elevations and properties of the porous medium. Thus, the model used in this study is, at least, partially validated. Specific objectives of this study are to investigate the: (i) beach groundwater response to wave motion and variable flow fields; (ii) beach profile evolution due to different wave conditions and porous media; (iii) effects of wave forcing on variable-density groundwater behavior; and (iv) effects of in/exfiltration on foreshore profile changes and groundwater dynamics in the nearshore zone.

2. Model description

2.1. Simulation of high-frequency wave motion and beach morphology

The hydrodynamic model, consisting of the two-dimensional continuity and momentum formulations of the incompressible RANS equations, k–ε turbulence closure and VOF method, was outlined by Bakhtyar et al. (2011).

The sediment transport model was discussed in detail in Bakhtyar et al. (2011). The surf and swash regions are highly complex, and none of the existing sediment models using the empirical approach