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Numerical experiments on breaking waves on contrasting beaches using a two-phase flow approach

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ABSTRACT

A mechanistic understanding of beach environments needs to account for interactions of oceanic forcing and beach materials, in particular the role of waves on the evolution of the beach profile. A fully coupled two-phase flow model was used to simulate nearshore fluid-sediment turbulent flow in the cross-shore direction. It includes the Reynolds-Averaged Navier–Stokes equations and turbulent stress closures for each phase, and accounts for inter-granular stresses. The model has previously been validated using laboratory-scale data, so the results are likely more reliable for that scale. It was used to simulate wave breaking and the ensuing hydrodynamics and sediment transport processes in the surf/swash zones. Numerical experiments were conducted to investigate the effects of varying beach and wave characteristics (e.g., beach slope, sediment grain size, wave periods and heights) on the foreshore profile changes. Spilling and plunging breakers occur on dissipative and intermediate beaches, respectively. The impact of these wave/beach types on nearshore zone hydrodynamics and beach morphology was determined. The numerical results showed that turbulent kinetic energy, sediment concentrations and transport rate are greater on intermediate than on dissipative beaches. The results confirmed that wave energy, beach grain size and bed slope are main factors for sediment transport and beach morphodynamics. The location of the maximum sediment transport is near the breaking point for both beach types. Coarse- and fine-sand beaches differ significantly in their erosive characteristics (e.g., foreshore profile evolutions are erosive and accretionary on the fine and coarse sand beaches, respectively). In addition, a new parameter (based on main driving factors) is proposed that can characterize the sediment transport in the surf and swash zones. The results are consistent with existing physical observations, suggesting that the two-phase flow model is suitable for the simulation of hyper-concentrated mixed water-sediment flows in the nearshore. The model thus has potential as a useful tool for investigating interactions between nearshore hydrodynamics and beach morphology.

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1. Introduction

Nearshore zones are highly dynamic systems that are characterised by marked fluctuations in salinity, local sediment budget, and foreshore profile changes [1,2]. Surf and swash zones with an economic or social interest are generally subject to human intervention, leading to changes in the system ecology [3]. Therefore, the nearshore area needs to be managed efficiently. Assessing the impact of oceanic forcing on sediment transport is essential for understanding the environment in all coastal zones [4].

The quantification of nearshore hydro- and morphodynamics is a prerequisite for coastal engineering design. Wave shoaling/breaking and its effects on sediment transport in the nearshore zone are fundamental for modelling beach morphology [1]. In the design and maintenance of marine structures, for example, coastal engineers need to estimate beach erosion/accretion due to wave motion. Due to the practical and theoretical significance of morphodynamics, combined fluid and sediment transport models of the surf and swash zones have generated considerable interest [2]. In particular, attention has been paid to nearshore motion, since sedimentation controls beach evolution.

Despite its importance, an accurate and complete description of the interactions between sea-level oscillations and sediments in

Abbreviations: NS, Navier–Stokes; RANS, Reynolds-Averaged Navier–Stokes; SWL, still water level; TKE, turbulent kinetic energy; VOF, volume-of-fluid.

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Nomenclature

$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$	empirical constants, –
C_D, C_L	drag and lift coefficients, respectively, –
d	still water depth, L
D_{50}	50th percentile of the sediment diameter distribution, L
E_f	wave energy flux, MT^{-1}
E_w	wave energy, MT^{-2}
F	fluid volume, $L^3\,L^{-3}$
F_s	influence of the sediment phase on the turbulence, $L\,T^{-2}$
g	magnitude of gravitational acceleration, $L\,T^{-2}$
h	water depth, L
h_{max}	maximum water depth, L
H	wave height, L
H_0	wave height in deep water, L
$\mathbf{k}$	unit vector in the vertical direction, –
k	turbulent kinetic energy, $L^2\,T^{-2}$
k_{max}	maximum turbulent kinetic energy, $L^2\,T^{-2}$
L_0	length of incident waves in deep water, L
L	model domain length, L
$\mathbf{M}$	hydrodynamic inter-phase forces (drag and lift forces), $ML^{-2}\,T^{-2}$
P	pressure, $ML^{-1}\,T^{-2}$
t	time, T
T	wave period, T
$\mathbf{T}_s$, $\mathbf{T}_f$	sediment and fluid phase stress tensors, respectively, $ML^{-1}\,T^{-2}$
$\mathbf{V}_f$, $\mathbf{V}_s$	fluid and sediment velocity vectors, respectively, $L\,T^{-1}$
x, z	horizontal and vertical directions, L

Greek symbols

$\tan(\theta)$	bed slope, –
ω	angular frequency, T^{-1}
φ_f, φ_s	volume fraction of fluid and sediment, respectively, $L^3\,L^{-3}$
φ_{sm}	maximum static sediment concentration, $L^3\,L^{-3}$
ν	kinematic viscosity, $L^2\,T^{-1}$
ν_t	eddy viscosity, $L^2\,T^{-1}$
ε	turbulence dissipation rate, $L^2\,T^{-3}$
Δt	time step, T
ρ_f, ρ_s	fluid and sediment densities, respectively, ML^{-3}
ξ, ς	Surf similarity and surf scaling parameters, respectively
σ_k, σ_ε	empirical constants, –
γ	internal friction angle of sediment, –
$D()/Dt$	material derivative, T^{-1}
$\nabla \equiv (\partial/\partial x, \partial/\partial z)$	gradient vector, L^{-1}

the complex coastal zones (surf and swash zones) is still partially unknown [1,5–7]. While recent studies tried to determine the processes active in this region, nearshore sediment transport remains a weakly understood area that is mainly untreated in existing studies [8,9]. The complex nature of hydrodynamic and sediment transport processes that occur in the nearshore zone, such as wave breaking and associated turbulence and mixed sediment-fluid flow, requires an accurate description of the flow characteristics [10]. In order to predict the evolution of beach morphology with reasonable accuracy and to understand the key processes governing the transport of sediments, comprehensive investigations are needed to study the interactions between breaking waves and swash motions and sediments.

Nearshore zone hydrodynamics depends on wave characteristics and bed slope [11]. There is considerable variation in the dynamics of flows due to spilling and plunging breakers, as well as the major differences in beach profiles between intermediate and dissipative beaches [12]. Aagaard and Hughes [8] postulated that generally two types of swash regime exist: (i) on steep beaches and (ii) on gentle beaches. On steep beaches, plunging breakers occur and the beach type is intermediate, while on the gentle beaches the breaker and beach type are spilling and dissipative, respectively [11,13]. Other parameters that determine the beach type are sediment grain size and wave energy, the latter being proportional to wave characteristics [1,2].

Empirical formulas for sediment transport on beaches, although useful, are limited due to the inherent process interactions and complexity [14]. Similarly, the shallow water equations and Boussinesq-based models that are commonly used in coastal applications are not appropriate for simulating detailed nearshore sediment transport and hydrodynamics [2]. Surf and swash motions vary markedly in both the cross-shore and vertical directions. As these models assume a hydrostatic pressure distribution (zero vertical velocity), they cannot provide realistic details of combined sediment/water flows. Additionally, since the intensity of the turbulence and sediment concentrations are both high, motions of the fluid and sediment phases are tightly coupled [13]. When sediment concentration and bed shear stress magnitude are relatively high (as in the inner surf and swash zones), the inter-granular stress becomes as significant as the fluid-sediment interactions. Existing single-phase flow models cannot simulate inter-granular stresses and average behaviour of particles, and therefore are not able to capture beach morphology accurately. More sophisticated numerical models are required to reproduce in more detail the physics of nearshore motion and interactions between fluid and sediment, and particle and particle.

Recently, two-phase flow models have been recognized as potentially valuable tools for modelling complex coastal engineering and open channel problems. There are basically two approaches for two-phase flow modelling: (i) the Lagrangian approach, which follow sample particles and (ii) the Eulerian approach, in which the particles are treated as a continuum [15]. Two-phase flow models that treat separately the sediment and fluid phases provide a sound basis for simulating interactions between phases. Several sediment-laden, two-phase flow models have been reported for simulations of open channel flows [16–22] and sediment transport in estuaries [23]. Such models were used to investigate effects of oscillatory flows on sediment transport in coastal areas [24–26]. Asano [27] presented a two-phase flow model based on the principles of the Kobayashi and Seo model [28] in which the vertical velocity of particles was approximated by empirical relations. Dong and Zhang [29] presented a two-phase flow (with eddy viscosity) model, capable of simulating the fluid and particle motions in oscillatory sheet flows. Liu and Sato [30,31] simulated the sediment transport rate under combined wave/current conditions and under various asymmetric sheet flows. Hsu et al. [25] and Hsu and Hanes [26] developed a fully coupled two-phase flow model to model fluid-sediment oscillatory sheet flow and bed profile changes. Additional description and discussion of the two-phase flow modelling approaches that have been used to simulate beach morphology in the coastal area were summarized by Bakhtyar et al. [13,15].

Bakhtyar et al. [13,15,32] developed a two-dimensional (cross-shore), two-phase flow model for simulating nearshore hydrodynamics and morphology on an impermeable beach taking into account fluid-sediment interactions. They used the model to

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