Numerical Model of Wave-induced Coastal Hydrodynamic and Morphodynamic Processes

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ABSTRACT

The aim of the present research is to present a numerical model for the simulation of wave hydrodynamics coupled with sediment transport and bed morphodynamics. The model is based on the formulation of three-dimensional (3D), large-eddy simulations with emphasis on the development of a morphological module under wave forcing. The numerical model has been effectively validated against numerical studies and laboratory measurements involving wave motion, sediment transport and morphodynamical evolution. Wave propagation and breaking are examined over an idealized beach with fixed bed of constant slope 1/15, as well as the corresponding suspended sediment transport. Moreover, the sediment transport mechanisms and the resulting morphological evolution of rippled beds were also examined under oscillatory flow conditions generated by non-breaking waves, with numerical results of ripple creation and growth presented.

KEY WORDS: Sediment transport; wave propagation; ripples; Navier-Stokes; immersed boundary; morphology evolution.

INTRODUCTION

The primary coastal process that causes shoreline erosion is the creation of strong bed shear stresses in the surf zone, which induce sediment motion and currents (cross-shore and long-shore) that carry the sediment offshore. This process continues until scouring phenomena take place and wave energy dissipation is in equilibrium with the eroded bed. A significant number of numerical models have been developed in recent years to simulate coastal processes. Dally & Dean (1984) were among the first to attempt the numerical modeling of coastal sediment transport, developing a mathematical model for coastline evolution. Depending on the wave and sediment characteristics, their model had the ability to generate both normal and storm-type beach profiles. Large-Eddy Simulation (LES) results combined with sediment transport over prototypical long-wave ripples, were presented by Zedler & Street, (2006). The authors concluded that the flow over such longer ripples is quite similar to the flow over vortex ripples. Marieu et al. (2008) developed a two-dimensional Reynolds-Averaged Navier-Stokes numerical model to simulate the development and morphological evolution of ripples, examining phenomena of ripple creation, development, merging, and annihilation. They also investigated the effect of the initial bed geometry on the morphological evolution, deducing that under the same flow characteristics the bed reaches the same equilibrium state regardless of the initial one. Kraft et al. (2011) simulated numerically the free-surface turbulent flow in a channel as well as the sediment transport over a rippled bed, using LES. In addition, they studied the morphological evolution of the rippled bed using the Level-Set method, and they used three different pickup relations for the sediment erosion. More recently, Jacobsen & Fredsøe (2014) analyzed the hydrodynamics of wave breaking combined with sediment transport over a fixed bottom of constant slope. They presented an empirical relationship for the phase lag between the breakpoint and the initiation of the setup, mentioning also that this phase lag determines the maximum values of the undertow and the bed shear stress. Leftheriotis & Dimas (2017) presented LES results of a three dimensional (3D) oscillatory turbulent flow, sediment transport and morphodynamics for the creation and development of ripples on a sandy bottom. It was shown that this model had the ability to capture ripple development, resulting in ripple lengths which were in agreement with those predicted by empirical equations. They concluded that under the same hydrodynamic forcing, the equilibrium state of the bed is the same, regardless of the initial bed form. Dimas & Leftheriotis (2019) conducted a parametric analysis for oscillatory flow and sediment transport over a fixed sandy bottom with ripples using the LES and 3D Immersed Boundary (IB) method. They found that the relative contribution of bed load versus suspended load on the total sediment load depends on both the mobility parameter and the non-dimensional sediment grain diameter. Finally, in their simulations the prediction of the vortex suspension parameter, $P_v$, in distinguishing between bed and suspended load dominance. Dimas and Koutrouveli (2019) presented numerical results for wave propagation and spilling breaking over beach profiles of varying slopes using the IB and the Level-Set method with the bed profile and the free surface being immersed in a Cartesian grid. They found that the breaking depth and the wave height decreased as the beach slope increased or the surf-similarity parameter decreased. The generation of vorticity at the level of the free surface was mainly attributed to advection and secondarily to gravity.