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Large-eddy simulation of turbulent flow and sediment transport induced by wave propagation and breaking over constant-slope beach

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ABSTRACT

Wave-induced hydrodynamic and sediment-transport processes in nearshore regions are crucial in the design of coastal protection measures. Waves in the coastal zone interact with the seabed, resulting in wave breaking, wave-generated currents, wave boundary layer development and sediment transport in the form bed and suspended loads. These processes have the potential to cause bed morphological changes, such as small-scale bed formations, i.e. ripples, or large-scale ones, i.e. berms and seasonal beach profiles. Occasionally, large-scale bed morphological changes may cause beach erosion and/or threaten the stability of coastal infrastructures. These issues motivate the need for predictive models that explicitly couple hydrodynamics and sediment transport. In this work, such an in-house numerical model was developed and results are presented of flow and suspended sediment transport induced by breaking waves over a constant-slope beach.

1. Methodology

1.1. Hydrodynamics

The combined water and air flow is modeled as one-fluid flow governed by the incompressible Navier-Stokes equations, appropriate to model flow in porous media (Liu et al., 1999). The formulation is similar to the approach of large-eddy simulation (LES) where the subgrid scales (SGS) of the flow, resulting from wave breaking are not resolved, but their effect on the resolved flow scales is modeled by an SGS eddy-viscosity model. The resulting equations are:

$$\frac{\partial u_i}{\partial x_i}=0 \tag{1}$$

$$\frac{1+c_A}{n}\frac{\partial u_i}{\partial t}+\frac{1}{n^2}\frac{\partial}{\partial x_j}\left(u_i u_j\right)=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}-\frac{\partial \tau_{ij}}{\partial x_j}+\frac{1}{\mathrm{Re}}\frac{1}{n}\frac{1}{\rho}\frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right)+\frac{\delta_{i3}}{\mathrm{Fr}^2}+f_i-\frac{\left(1-n^2\right)}{n^3}\frac{v}{D_{50}^2}\frac{20}{\mathrm{Re}}u_i-1.1\left(1+\frac{7.5}{\mathrm{KC}}\right)\frac{1-n}{n^3}\frac{1}{D_{50}}u_i\sqrt{u_i u_i} \tag{2}$$

where t is time, the Cartesian coordinates x_i correspond, hereafter, to the streamwise ($x = x_1$), spanwise ($x = x_2$), and vertical ($z = x_3$) directions, u_i are the resolved velocity components ($u = u_1$, $v = u_2$, $w = u_3$), p is the total pressure, i.e., the sum of the dynamic and hydrostatic pressure, ρ is the normalized fluid density, μ is the normalized fluid dynamic viscosity, v, is the normalized fluid kinematic viscosity, δ_{i3} is the Kronecker's delta function, Fr is the Froude number, τ_{ij} are the SGS stresses, related to the LES, Re is the Reynolds number, c_A is the added mass coefficient (calculated by $c_A = 0.34(1\text{-}n)/n$, following van Gent, 1995), n is the effective porosity, D_{50} is the mean grain diameter of the porous media, and, KC is the Keulegan-Carpenter number. The external forcing function, f_i, is associated with the implementation of the Immersed-Boundary (IB) method for the enforcement of no-slip boundary conditions on immersed solid surfaces. Outside the porous media, in the clear fluid region, it is n=1 and $c_A = 0$. In Eqs (1) and (2), lengths are non-dimensionalized by d_0 which is the characteristic offshore boundary depth and velocities by $(gd_0)^{1/2}$, therefore, Fr = 1 and Re = $d_0(gd_0)^{1/2}/v_w$ where v_w is the water kinematic viscosity. The SGS stresses are modelled by the standard eddy-viscosity Smagorinsky model (Smagorinsky, 1963).

1.2. Sediment Transport

The evolution of sediment in suspension was modeled using a dimensionless advection-diffusion equation for the volumetric concentration, c, of the suspended sediment:

$$\frac{\partial c}{\partial t} + u_j \frac{\partial c}{\partial x_j} - w_s \frac{\partial c}{\partial x_3} = \frac{1}{\sigma \mathrm{Re}} \frac{\partial^2 c}{\partial x_j \partial x_j} - \frac{\partial \chi_i}{\partial x_i} + f_c \tag{3}$$

where w_s is the dimensionless settling velocity of the sediment calculated according to Hallermeier (1981), χ_i is the SGS turbulent flux of sediment, σ is the Schmidt number, and f_c is a source term associated with the implementation of the IB method for the enforcement of the appropriate sediment concentration boundary condition on the bed surface.

2. Results

In Figure 1, a typical instantaneous snapshot of the wave breaking process on a plane beach with constant-slope 1/15 (after six incident waves have already broken) is shown along with the volumetric concentration of sediment in suspension. The concentration of the suspended sediment is higher primarily in the swash zone forming a near-bed, landward advecting plume. In the offshore, suspended-sediment entrainment can be observed primarily near the bed beneath wave troughs.

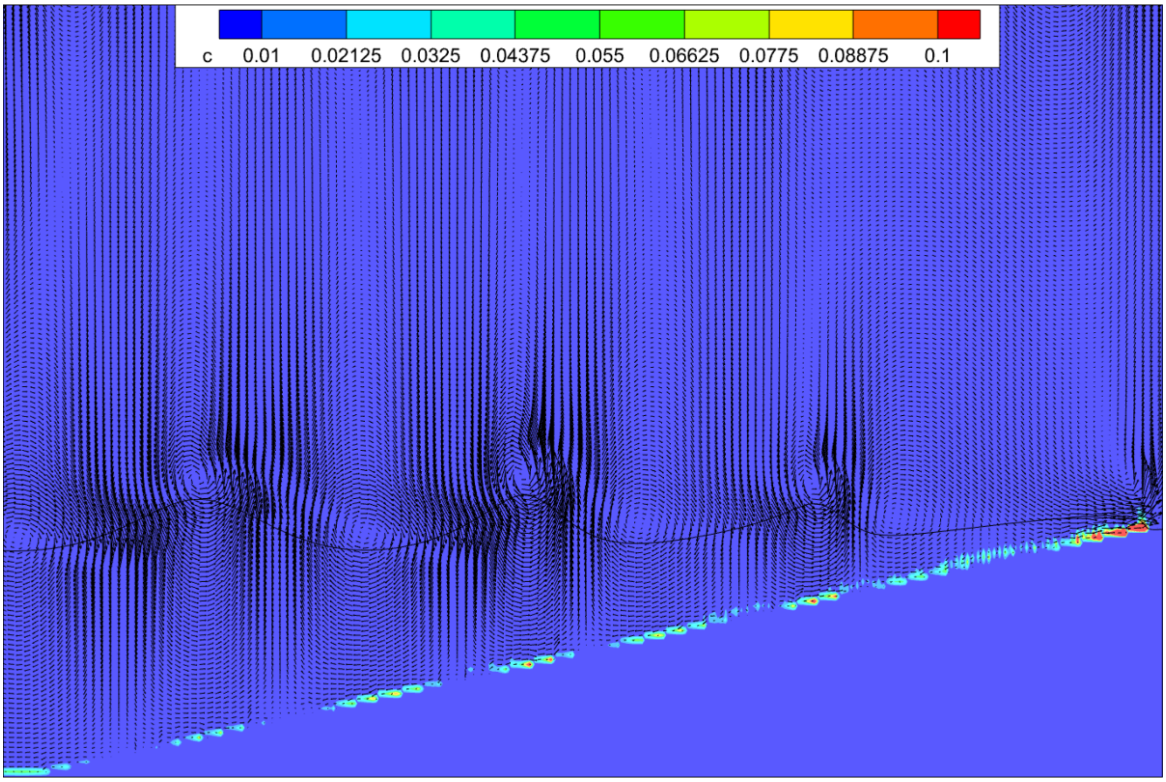

Fig. 1. Wave breaking on a beach with constant slope 1/15. The solid black line corresponds to the water-air interface, the contours present the volumetric concentration, c, of the suspended sediment, and the vectors indicate the velocity field.

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