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Large-Eddy Simulation of Turbulent Oscillatory Flow and Mixed-Grain Sediment Transport Over Fixed Bed Ripples

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INTRODUCTION

Mixed-grain sand significantly impacts sediment transport by influencing hydrodynamic interactions, bedform evolution, and sediment mobility. Natural sediment beds contain varying grain sizes, leading to complex transport mechanisms that affect bedload and suspended sediment flux, complicating sediment transport predictions. Grain-specific critical shear stress varies due to differences in particle protrusion, drag forces, and near-bed turbulence.

Studies highlight the importance of considering these variations when modeling sediment transport, as they directly impact the initiation and movement of different grain sizes.
Bed roughness, influenced by grain-size heterogeneity, plays a crucial role in sediment mobilization. Coarser grains increase flow resistance, enhancing transport rates and altering wave-boundary layer dynamics. These interactions significantly impact ripple formation in oscillatory flows, where vortex structures shape the seabed. The mobility parameter ψ and the normalized sediment size a_o/D_g control ripple evolution, affecting sediment transport efficiency.

This study examines the impact of mixed-grain sediments on transport processes, integrating numerical simulations to assess the influence of grain-size variability on sediment dynamics in coastal and offshore environments.

METHODOLOGY

In realistic sediment transport problems, one has to deal with a grain-size distribution curve that follows a log-normal distribution (Fredsøe and Deigaard, 1992), which is discretized in “k” number of fractions.

This study employs Large-Eddy Simulation (LES) to investigate the dynamics of mixed-grain sand transport under oscillatory wave-induced flow over fixed bed ripples. The governing fluid equations, rendered dimensionless, are the continuity and the Navier-Stokes, and they are solved numerically, incorporating the Smagorinsky eddy-viscosity model for the subgrid-scale (SGS) stresses. The immersed boundary (IB) method (Dimas and Chalmoukis, 2020) is applied to enforce the non-slip boundary condition on the seabed.

Bedload transport is computed using the formulation in Engelund and Fredsøe (1976), adapted for grain-size fractions, while suspended sediment evolution follows an advection-diffusion equation, with settling velocities calculated separately according to Hallermeier (1981) for each sediment fraction “k”. A hide-exposure factor (Wu et al., 2002) refines the critical Shields parameter, accounting for size-dependent entrainment thresholds by calculating the probabilities of each “k” fraction being hidden or exposed by the other fractions. Numerical discretization in time utilizes a two-stage time-splitting scheme combined with second-order Adams-Bashforth method. External wave forcing follows a second-order Stokes wave model, ensuring realistic flow boundary conditions. Numerical discretization in space is based on a 2nr-order central finite-difference scheme; a typical computational domain is shown in Fig. 1.

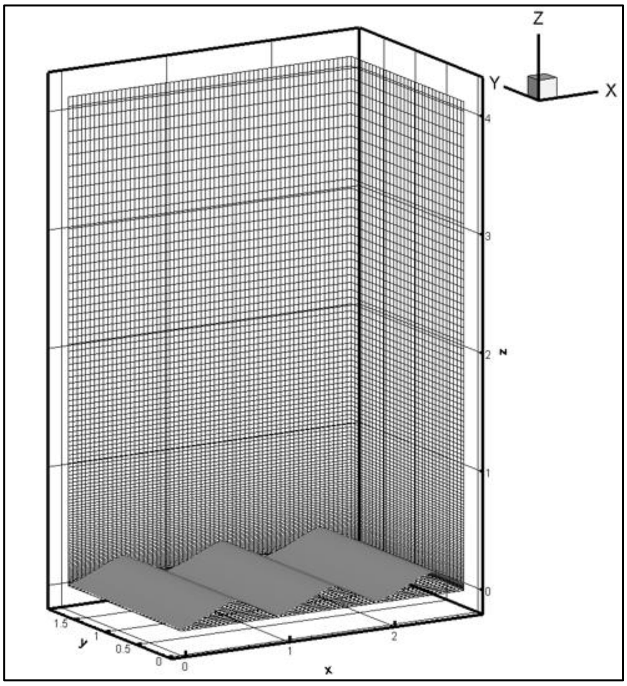

Figure 1 Sketch of a typical computational domain with Cartesian grid for the simulation of oscillatory flow over ripples. The rippled bed is immersed in the Cartesian grid.

The mixed grain-sand (comprising 5 fractions with diameters D_{10}=0.25 mm, D_{30}=0.35 mm, D_{50}=0.44 mm, D_{70}=0.53 mm, and D_{90}=0.66 mm) and the flow parameters in the experiments by Van der Werf et al. (2007) were used and out model was validated by comparison with the corresponding experimental data of sediment transport rates, vorticity structures, and concentration profiles. Results provide insights into size-selective sediment transport, phase-lag effects, and morphodynamic responses under varying hydrodynamic conditions.

RESULTS AND DISCUSSIONS

The LES simulations reveal distinct transport mechanisms for mixed-grain sediment under oscillatory flow, with bedload and suspended load exhibiting strong size-selective behavior. Analysis of Shields parameter variations shows that incorporating the hiding-exposure factor (Wu et al., 2002) significantly alters entrainment thresholds: finer grains require higher shear stress to mobilize, while coarser grains experience reduced thresholds due to preferential exposure. The velocity and vorticity fields (Fig. 2) demonstrate strong vortex structures that peak near the bed during flow reversal, enhancing sediment uplift and entertainment (Fig. 3).

Fine-grained fractions (D_{10}–D_{30}) experience prolonged suspension due to turbulence, whereas coarser fractions (D_{70}–D_{90}) primarily contribute to bedload transport, particularly at ripple crests where shear stress peaks. The suspended load is highest at flow reversal phases, with vortex-induced uplift enhancing sediment entrainment. Period-averaged velocity (Fig. 2) and sediment flux profiles demonstrate that suspended transport is dominated by fine fractions, while coarser grains display onshore-directed bedload transport, reinforcing morphodynamic stability of ripple formations (Fig. 4). The comparison with van der Werf et al. (2007) experimental data shows strong agreement, validating the numerical approach. These findings highlight the role of grain sorting in transport dynamics, with turbulence-driven phase-lag effects altering net transport rates. The results have implications for coastal morphodynamics modeling, improving predictions of sediment redistribution in natural environments.

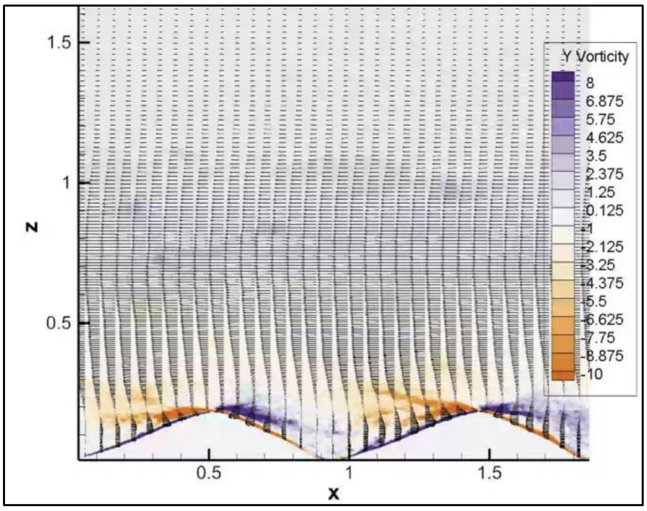

Figure 2 The period- and spanwise-averaged velocity field (vectors) and Y vorticity field.

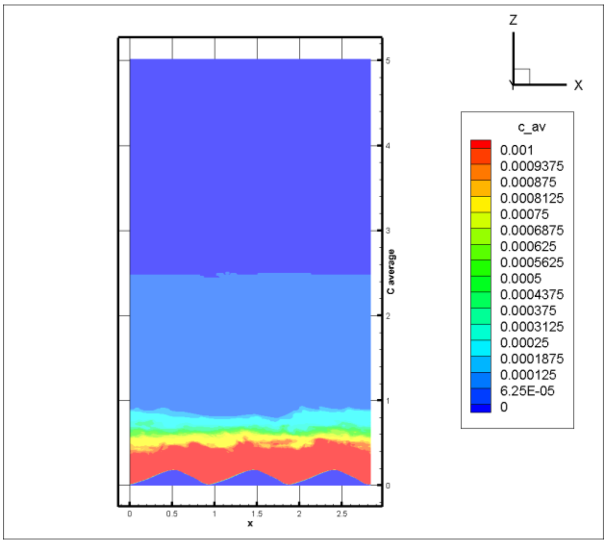

Figure 3 Period-average suspended sediment (c) of the smallest sediment fraction of diameter size 0.25 mm.

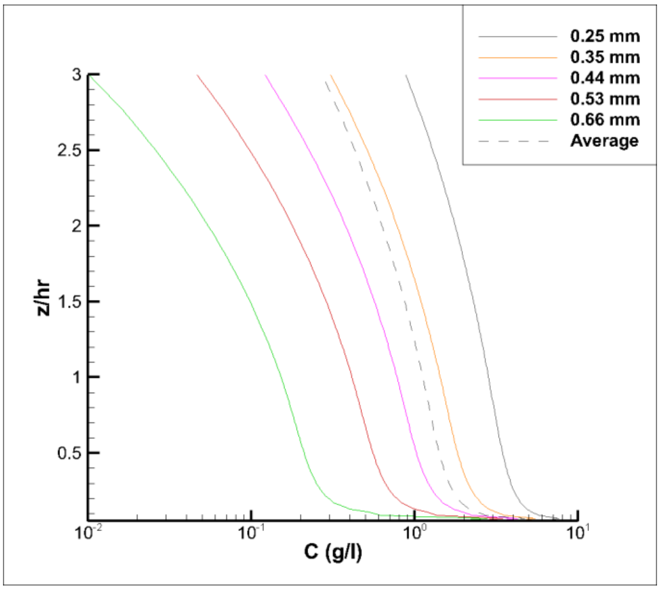

Figure 4 Profiles of the mean suspended sediment concentration of each sediment size fraction up to 3 hr.

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