MIXED-GRAIN SAND TRANSPORT INDUCED BY TURBULENT OSCILLATORY FLOW OVER FIXED RIPPLES

Ioannis-Gerasimos Tsipas, University of Patras, up1054975@ac.upatras.gr
Georgios A. Leftheriotis, University of Patras, gleytheriot@upatras.gr
Athanassios A. Dimas, University of Patras, adimas@upatras.gr

INTRODUCTION

Mixed-grain sand significantly impacts sediment transport by influencing hydrodynamic interactions, sediment mobility, and bedform evolution. 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, such as Dey and Papanicolaou (2008) AND de Leeuw et al. (2020), 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 and the normalized sediment size a_0/D_g (a_o is the orbital amplitude of the external oscillatory flow and D_g is the sand grain diameter) control ripple evolution, affecting sediment transport efficiency.

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

METHODOLOGY

Realistic coastal sediments are described by a grain-size distribution curve that follows a log-normal distribution (Fredsøe and Deigaard, 1992); in our method this distribution is discretized into “*k*” equal-mass fractions.

This study employs Large Eddy Simulation (LES) to investigate the dynamics of mixed-grain sand transport under oscillatory wave-induced flow over 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 (Fig. 1). Bedload transport is computed using the Engelund and Fredsøe (1976) formulation, adapted for grain-size fractions, while suspended sediment evolution follows an advection-diffusion equation (Dimas & Leftheriotis, 2019), with settling velocities calculated according to Hallermeier (1981), for each sediment fraction size “*k*”. For the available concentration for suspension, two cases of boundary conditions were implemented and compared: the semi-empirical formulation in Fredsøe and Deigaard (1992) developed for the mean diameter(D_{50}), and the empirical formulation in Van Rijn (1984), adjusted for each “*k*” fraction.

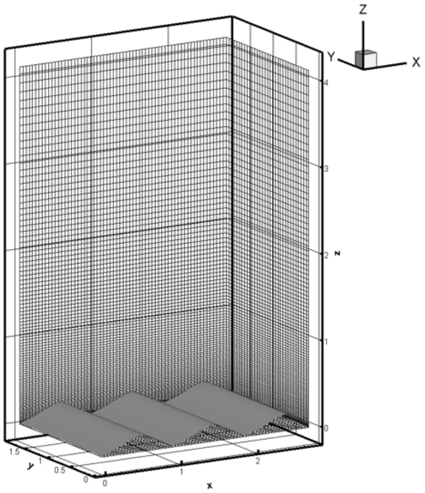

Figure 1 Sketch of a typical computational domain with Cartesian grid, used in the simulations of oscillatory flow over ripples. The rippled bed is immersed in the Cartesian grid.

Numerical discretization utilizes a two-stage time-splitting scheme combined with an explicit second-order Adams-Bashforth method for the first stage and an implicit projection method for the second stage. External wave forcing follows a second-order Stokes wave model, ensuring realistic flow boundary conditions.

Simulation parameters are calibrated against the van der Werf et al. (2007) experimental data, with validation performed through comparisons 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 DISCUSSION

The LES simulations reveal distinct transport mechanisms for mixed-grain sediment under oscillatory flow, with bedload and suspended load exhibiting strong size-selective behavior. Contours of y-vorticity with superimposed velocity vectors (Fig. 2) show vortex shedding from ripple crests and recurrent separation over lee slopes. 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 (Fig. 3). Period-averaged velocity 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. The comparison with the experimental data in van der Werf et al. (2007) shows strong agreement, validating the numerical approach (Fig. 4). 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.

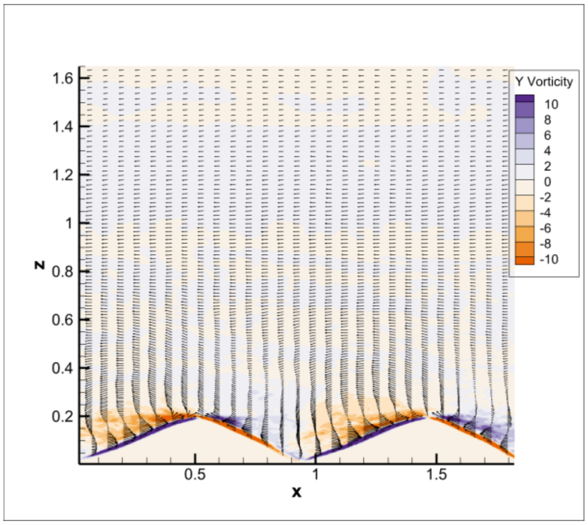

Figure 2 Period- and spanwise-averaged velocity field (vectors) and Y vorticity field during the 149th wave period.

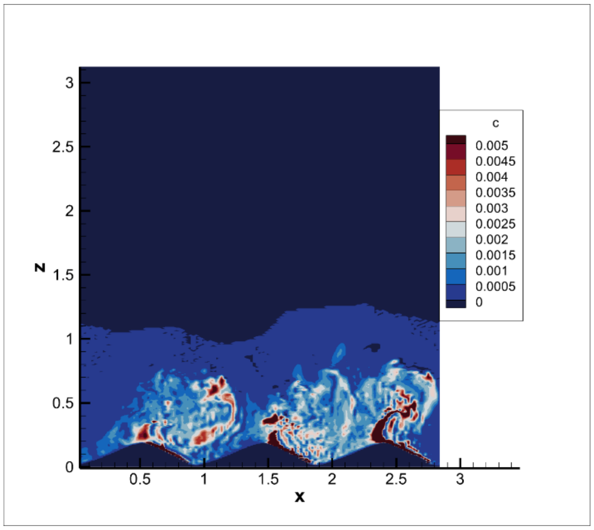

Figure 3 Instantaneous suspended sediment concentration (c) of the mean fraction after 1.5 wave periods.

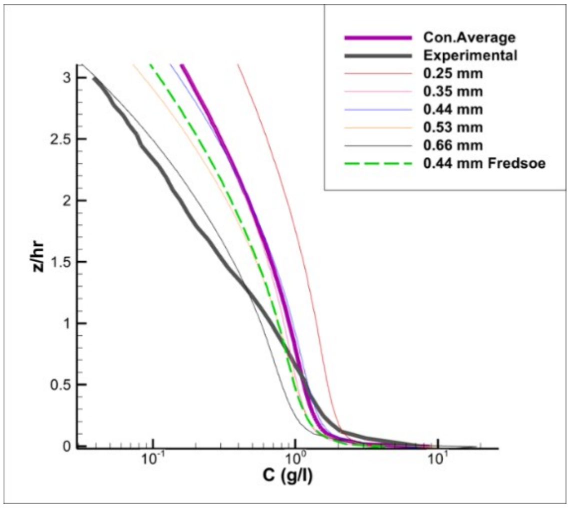

Figure 4 Concentration profiles of suspended sediment for each grain-size fraction, as well as the average of all fractions, obtained using Van Rijn's formulation. The dashed line represents the profile from the Fredsøe formulation evaluated for D_{50}.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's (EU) Horizon Europe Framework Programme (HORIZON) under Grant Agreement No. 101072443 as a MSCA Doctoral Network (HORIZON-MSCA-2021-DN-01).

REFERENCES

Dimas, Chalmoukis (2020): An adaptation of the immersed boundary method for turbulent flows over three-dimensional coastal/fluvial beds. Appl Math Model, vol. 88, pp. 905-915.

Dimas, A. A., & Leftheriotis, G. A. (2019). Mobility parameter and sand grain size effect on sediment transport over vortex ripples in the orbital regime. J. Geophysical Research: Earth Surface, 124(1), 2-20.

Fredsøe, J., & Deigaard, R. (1992). Mechanics of Coastal Sediment Transport. World Scientific.

Hallermeier, R. J. (1981). Terminal settling velocity of commonly occurring sand grains. Sedimentology, 28(6), 859-865.

van der Werf, J. J., Doucette, J. S., O'Donoghue, T., & Ribberink, J. S. (2007). Detailed measurements of velocities and suspended sand concentrations over full-scale ripples in regular oscillatory flow. Journal of Geophysical Research: Earth Surface, 112(F2).

van Rijn, L. C. (1984). Sediment transport, part II: Suspended load transport. Journal of Hydraulic Engineering, 110(11), 1613-1641.

De Leeuw, J., Lamb, M. P., Parker, G., Moodie, A. J., Haught, D., Venditti, J. G., & Nittrouer, J. A. (2020). Entrainment and suspension of sand and gravel. Earth Surface Dynamics, 8(2), 485-504.

Dey, S., & Papanicolaou, A. (2008). Sediment threshold under stream flow: A state-of-the art review. KSCE J. Civil Engineering, 12(1), 45-60.