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Causality between fluid motions and bathymetric features

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Can morphodynamic problems be solved using a first-principles approach in multiphase fluid mechanics? This is the holy grail for many sediment transport researchers but has yet to be achieved in practice. Using a fully resolved direct numerical simulation for turbulent flow over a bed of spheres, the study of Scherer *et al.* (*J. Fluid Mech.*, vol. 930, 2022, A11) investigates the onset of morphodynamics from a statistically flat bed. The study shows that the formation of streamwise-aligned sediment ridges is due to large-scale turbulent streaks in the logarithmic layer, which drives local sediment sweeps and bursts. The study provides a solid physical justification for introducing initial perturbations in other reduced-complexity models and opens up new perspectives for simulating sediment transport and morphodynamic problems using high-fidelity models.

Key words: sediment transport, turbulent flows

1. Introduction

Modelling the evolution of subaqueous topography, or namely the morphodynamics, in rivers and oceans is highly challenging due to the complex sediment transport processes resulting from the coupled turbulent two-phase fluid dynamical system for a wide range of particle concentrations. Nearly all the existing morphodynamic models require prescribed bathymetric features (spatial variability). In large-scale morphodynamic modelling, these bathymetric features may naturally exist; e.g. the canonical sandbar, a shore-parallel morphodynamic feature, is formed due to the existence of a sloping beach as surface waves shoal and break causing a net landward sediment transport flux via the transformation of wave shapes and a seaward flux by the undertow currents (Sherwood *et al.* 2022). However, for many other morphodynamic features, particularly for those that scale with the water depth, wave orbital length (wave orbital velocity amplitude divided by angular frequency), or grain size, the pre-existence of bathymetric features may be assumed but they are not necessarily obvious, and often seem arbitrary. For instance, the formation of streamwise-aligned sand ridges (Ikeda 1981; Nezu & Nakagawa 1984) is observed to be driven by spanwise secondary flows in a statistically steady and fully developed channel

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flow without notable spatial variability other than the sidewalls. However, as the sidewall effect was dismissed in follow-up experiments by varying the channel width (Nezu & Nakagawa 1989), the linear stability analysis predicting the generation of secondary flows had to invoke prescribed initial bed perturbations of unknown origin (Colombini 1993), which were later attributed to variability in bed roughness (Colombini & Parker 1995). On the other hand, numerous experimental and numerical studies of turbulence show the generation of large-scale turbulent coherent structures. Specifically, large-scale streaks that exhibit organized and predictable characteristics may drive sediment transport and cause the formation of morphodynamic features. Until very recently, the causality between fluid motions and bathymetric features has remained difficult to address because it requires the use of first-principles simulations of prohibitively high computational cost. This is because sediment transport results from the coupling of turbulent flows, granular flow and fluid–particle interactions, and the morphodynamic evolution is the result of these nonlinear dynamics through spatial and temporal integration. If one insists on using first principles, a numerical simulation must span about four to nine orders of magnitude in length scale (from at least one or one-tenth of the grain size to 10–100 times the size of resolved morphodynamic features) and time scale. The difficulties in solving morphodynamic problems using first-principles governing equations has led many geomorphologists to develop alternative methods to predict and study morphodynamics based on a 'top-down' approach using emergent variables and self-organized pattern formation (e.g. Werner 1999; Murray 2007).

The development of fully resolved direct numerical simulation models for two-phase fluid–particle systems has made first-principles sediment transport simulations a reality (e.g. Kidanemariam & Uhlmann 2014; Vowinckel *et al.* 2019). By asking the right question regarding the onset of morphodynamics, the work by Scherer *et al.* (2022) provides an unprecedented example on how we can use the first-principles approach to solve an outstanding morphodynamic problem on the causality between secondary flow generation and the formation of sand ridges.

2. Overview

Sand ridges, sometimes called sand ribbons, or sand streaks are elongated flow-parallel bathymetric features with a regular spanwise spacing that scales with the flow depth (Blondeaux 2001; Seminara 2010). Sand ridges are ubiquitous in rivers, tide-dominant environments such as tidal flats (Williams *et al.* 2008) and continental shelves, and even in the deep ocean as unique bathymetric signatures of turbidity currents (Meiburg & Kneller 2010). Although ephemeral, similar streak patterns have been reported in the inner surf and swash zone during backwash (Conley & Inman 1992), which have been related to near-bed turbulent coherent structures similar to finger patterns (Huang & Hwang 2015; Kim *et al.* 2017). These unique flow-parallel features are important as they may be the precursor of other types of bedforms; they can locally divert and enhance sediment transport (Fagherazzi & Mariotti 2012) and benthic fluxes (Huettel, Ziebis & Forster 1996); and they are prominent features that can be preserved in the geological record.

Scherer *et al.* (2022) carry out a series of fully resolved direct numerical simulations for a statistically steady fully developed turbulent channel flow over a mobile bed of spherical particles at different Reynolds numbers and domain sizes, and prove that subaqueous streamwise-aligned sediment ridges are generated by large-scale turbulent streaks. This finding solves the causality problem on the formation of small-scale bathymetric features (Colombini 1993) and, in fact, provides a physical justification for introducing small perturbations in the initial condition of reduced-complexity models for morphodynamic modelling. The simulation results also reveal and clarify that large-scale turbulent streaks cause mean secondary flows in open-channel flow after appropriate streamwise and time averaging. The secondary flow generation is closely related to turbulent coherent structures and the study confirms the previous experimental observations that the formation of sand ridges does not need to be due to the sidewall effect (Nezu & Nakagawa 1989).

Scherer *et al.* (2022) also present clear evidence that, regardless of rough-wall or sedimentary flow or smooth-wall flow, turbulence generation in the boundary layer is a top-down process, in contrast with some earlier studies (e.g. Adrian, Meinhart & Tomkins 2000) suggesting that flow structures generated in the buffer layer migrate outwards to form larger coherent structures. The implication for reduced-complexity sediment transport simulation is profound, as the high numerical resolution constraint to resolve small near-bed coherent structures can be relaxed. However, appropriate near-bed modelling suitable for sediment transport dynamics is warranted. Furthermore, simulation results also reconfirm the importance of resolving the large-scale turbulent coherent structures in a turbulence-resolving simulation approach (or the secondary flows in a Reynolds-averaged model). This suggests that reduced-complexity sediment transport models need to go beyond the eddy-viscosity-type two-equation closure, and a three-dimensional large-eddy simulation approach is favoured. If the Reynolds-averaged approach is necessary for large-scale applications, the minimum requirement is perhaps a three-dimensional Reynolds-averaged formulation with a nonlinear (second-order) Reynolds stress closure.

3. Future

The fully resolved direct numerical simulations reported in Scherer *et al.* (2022) provide a rare example of using the first-principles approach with minimum closure assumptions to deliver a 'close the loop' study on turbulent flow, sediment transport and morphodynamics. Although the methodology used by the authors is of immensely high computational cost, by choosing the right morphodynamic question, significant insights into the onset of morphodynamic evolution are gained. The work proves the role of large-scale turbulent streaks in driving the instantaneous sweep and burst of sediment transport and leading to the formation of sediment ridges. Several broader implications to the modelling of a wide range of morphodynamic problems are summarized as follows.

With the rapid advancement of high-performance computing, it is reasonable to expect that, within the next few years, the fully resolved simulation will be used to investigate how sand ridges may further evolve into other types of larger bedforms in different flow scenarios and heterogeneity of particles. Perhaps more importantly, the findings from Scherer *et al.* (2022) will guide other reduced-complexity models (for an overview, see Balachandar (2009)) to simulate a variety of morphodynamic problems. For instance, the Euler–Lagrange point-particle models (e.g. Finn *et al.* 2016) and the Euler–Euler two-fluid models (e.g. Cheng, Hsu & Chauchat 2018; Mathieu *et al.* 2022) are both capable of simulating turbulent flow (large-eddy simulation) over a mobile sediment bed without including the Exner equation and empirical sediment fluxes. However, these two types of reduced-complexity models, despite being more computationally efficient, require additional closure assumptions on interphase momentum transfer and intergranular interactions.

Fully resolved simulations, like those reported by Scherer *et al.* (2022), provide complete benchmark datasets to validate these reduced-complexity models, and, once validated, these models can be used to simulate a variety of sediment transport problems, such as bedform evolution and migration, wave-driven sheet flows and scour around objects. Although sediment transport is a two-phase system, the study of Scherer *et al.* (2022) demonstrates that resolving turbulent coherent structures is the key to driving the formation of sediment ridges. Existing reduced-complexity models for sediment transport should ensure that an adequate methodology to either resolve or better parametrize the carrier flow turbulence remains the most important task.

Declaration of interests. The author reports no conflict of interest.

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