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Numerical simulation of large dunes in meandering streams and rivers with in-stream rock structures

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ABSTRACT

The evolution and migration of large dunes in a realistic intermediate-size experimental stream, the Saint Anthony Falls Laboratory (SAFL) Outdoor StreamLab (OSL), and two large-scale meandering rivers with in–stream rock structures are studied numerically using the SAFL Virtual StreamLab hydro-morphodynamic (VSL3D) model. Due to the challenges arising from mesh quality and large disparity in time-scales, coupled morpho- and hydro-dynamics simulations of bed forms has, for the most part, been restricted to sand wave amplitudes of few centimeters. In this work, we overcome such difficulties by employing the immersed boundary approach and a dual time–stepping technique of the VSL3D model [63]. The VSL3D employs the curvilinear immersed boundary (CURVIB) method along with a suspended sediment load module and is capable of simulating turbulent stratified flows coupled with bed morphodynamic evolution in realistic riverine environments with arbitrarily complex hydraulic structures. Turbulence is handled either via large-eddy simulation (LES) with the dynamic Smagorinski subgrid scale model or unsteady Reynolds-averaged Navier Stokes (URANS) equations closed with the $k-\omega$ turbulence model. Simulations in the intermediate-scale OSL channel, in which we also collected experimental morphodynamic data, show that LES can capture the evolution and migration of bed forms with characteristics that are in good agreement with experimental measurements. The URANS model, however, fails to excite the bed instability in the OSL channel but captures realistic dune evolution in the two large-scale meandering rivers. This finding is especially important as it demonstrates the potential of the VSL3D model as a powerful tool for simulating morphodynamic evolution under prototype conditions. To our knowledge, our work is the first attempt to simulate large-scale bed forms in waterways with an order of magnitude disparity in spatial scales, from the $\sim$2.7 m wide OSL channel to the 27 m wide rivers. Accordingly, the height of the simulated dunes ranges from $\sim$0.2 m to 2.0 m and the wavelength ranges from $\sim$0.1 m to 50 m for the OSL and large-scale rivers, respectively. For all cases the statistical properties of the simulated bed forms are shown to agree well with those of bed forms observed in nature.

1. Introduction

Continuous transport of bed material in natural waterways caused by turbulent flow can lead to the formation, growth, and migration of multi-scale bed forms. Once turbulence gives rise to the formation of bed forms they rearrange the geometry of a mobile-bed and ultimately influence the turbulent flow in many ways including creating a wake zone downstream of the wave crest, shedding of vortices over the crestline, and rearranging the near bed high and low shear zones [64]. The study of bed form dynamics can help to obtain insights into the response of riverine systems to different flow fields and flooding events. Dune migration in field-scale rivers can temporarily cause deep holes at dune troughs while an increase in bed elevation is also expected to happen near dune crestlines. Thus, when it comes to the prediction of scour hole depth in riverine systems (often under live-bed conditions) it is important to have insights into the amplitude, wavelength, and geometry of bed forms passing through the system. Its also important to note that bed forms dynamics can also significantly affect the ecology of the waterways [1,10,11,71].

Because of the importance of fluvial sediment transport mechanisms, numerous papers have been devoted to the study of bed form dynamics. These studies range from experimental/analytical to numerical investigations. The majority of studies aim to predict

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bed form shape and size in various river geometries and flow conditions. The simplest models are those that employ linear stability theory and are appropriate for describing very small scale bed forms with amplitude (Δ) of less than 1.0 cm (e.g. see [23,27–29,39,44,48,58,81]).

Computational studies investigating turbulent flow over artificially frozen bed form geometries seek to investigate the dynamics of coherent vortical structures and the effect of waveform geometry on turbulence in the absence of interactive coupling between the two. Such studies include, among others, the works of Blondeaux and Vittori [8], Scandura et al. [86], Barr et al. [6], Chang and Scotti [13], Best [7], Zedler and Street [101,102], Henn and Sykes [45], Chang and Scotti [14], Zou et al. [103], Yue et al. [100], Angelis et al. [3], and Chau and Bhaganagar [16]. Only a few works are devoted to simulating coupled flow and bed morphodynamics, resolving turbulent flow induced sediment transport mechanisms and the interaction between them. Chou and Fringer [18] employed an Arbitrary Lagrangian–Eulerian (ALE) method along with a LES model to simulate small-scale ripples ($O(\leq 2\text{ cm})$) induced by oscillatory waves. Escauriaza and Sotiropoulos [37] employed the ALE technique with the Detached Eddy Simulation (DES) method to simulate turbulent flow and morphodynamics of sand waves during their initial stages ($O(\leq 1\text{ cm})$). In a recent work, Nabi et al. [74] employed a LES-based coupled hydro- and morphodynamic model to simulate the sand wave development in a 1.5 m wide rectangular laboratory flume. They also systematically investigated the effect of sediment particle size on the geometrical shape of the numerically captured sand waves (less than 8 cm high). More recently, Khosronejad and Sotiropoulos [64] simulated the coupled stratified flow and bed morphodynamics of sand wave development in an laboratory flume that was experimentally observed by Venditti et al. [95]. They employed the curvilinear immersed boundary method of Khosronejad et al. [60] and showed that the initiation of sand waves is linked to the characteristics of turbulent flow over the flat bed. They also showed that the qualitative and quantitative characteristics of the simulated bed forms, whose amplitude was of the order of ~5 cm, were in good agreement with the experimental measurements.

As follows from the above literature review, past attempts to simulate numerically sand wave dynamics have been restricted to reproduce small-scale bed forms with amplitudes not exceeding few centimeters [15,18,37,65,75,84,91]. There are two major difficulties limiting the applicability of most numerical models to small-scale bed forms: (*i*) Most methods employ the ALE approach, which requires that the grid conforms to the boundary shape at all times. This requirement restricts the application of such methods to simulations of small amplitude bed forms for which the mesh deformation remains small at all times (for more details see [64]); and (*ii*) The time scale for the sediment transport process is about two orders of magnitude greater than that of the instantaneous turbulent flow field [73]. Given this different in time scale, the coupled simulation of large-scale bed form evolution, which could take up to months of physical time, can be extremely expensive regardless of the underlying numerical approach. In order to overcome these problems and simulate the development of large-scale bed forms we employ in this work the VSL3D model, which has the following capabilities: (*i*) It employs the CURVIB method to handle arbitrarily large deformations on the mobile bed. In the CURVIB framework we use two different grid systems: one structured background grid system for the flow field computations, and one unstructured grid system for discretizing and tracking the motion of the and sediment/water interface layer. The unstructured grid of the mobile bed can freely deform without influencing the quality of the background grid; and (*ii*) It features a dual time-stepping quasi-synchronization method (for more details see [63]) for decoupling the hydrodynamic and morphodynamic time-steps, which is essential for simulating cases requiring long period of physical time to reach equilibrium state (e.g. the large-scale bed form evolution in large rivers that could take up to a months to reach equilibrium). The VSL3D also incorporates both LES and URANS turbulence modeling strategies [54,55].

The capabilities of the VSL3D to carry out high-fidelity LES of the coupled co-evolution of the flow and sand waves in a straight laboratory flume was recently demonstrated by Khosronejad and Sotiropoulos [64]. In this study the VSL3D was applied to a case studied experimentally by Venditti et al. [94] using very fine computational grids (up to 90 million grid nodes) and fully synchronized hydro-morphodynamic simulation. It was shown that the model is able to capture the observed in the laboratory initiation, growth and migration of sand waves with very good qualitative and quantitative accuracy. More specifically, the computed temporal evolution of sand wave amplitude, celerity, wave length and degree of three-dimensionality were shown to be in excellent agreement with the data of Venditii et al. [94]. The computed results were further analyzed to elucidate the role of near-bed sweeps in de-stabilizing the initially flat bed, clarify the process via which bed forms migrate, and further elucidate the mechanisms via which horseshoe-shaped coherent structures induced by the migrating bed-forms grow and affect the flow at the free-surface. The work of Khosronejad and Sotiropoulos also provided new insights into the statistical properties of sand waves and their distinct signature into the flow velocity spectra as function of distance from the bed [64]. It should be noted, however, that all simulations reported in [64] were carried out for a straight, laboratory-scale flume with bed form amplitudes not exceeding ~6 cm.

In this paper we seek to demonstrate for the first time that the VSL3D model can be a powerful hydraulic engineering computational tool for simulating bed form dynamics, with amplitudes ranging from centimeters to meters, in real-life meandering streams and large rivers with arbitrarily complex, in-stream rock structures. We also seek to investigate the level of turbulence modeling sophistication required to excite the bed instability in mobile-bed systems of varying scale. To that end, we simulate dune dynamics in three different waterways with and without embedded in–stream rock structures: (*i*) the intermediate-scale stream presently installed in the St. Anthony Falls Laboratory (SAFL) Outdoor StreamLab (OSL), with amplitudes and wavelengths in the range of ~0.1–0.2 m and ~0.1–1.5 m, respectively; (*ii*) a representative large-scale gravel bed river with dune amplitudes and wavelengths in the range of ~0.5 m and ~20 m, respectively; and (*iii*) a representative large-scale sand bed river with corresponding dune characteristics of ~1.5 m and ~30 m, respectively. In addition to the numerical simulations we also report herein experimental measurements of bed form characteristics for the OSL case, which we employ to validate the VSL3D predictions. Our simulations show that in the intermediate-scale system LES is essential for exciting the bed instability and giving rise to rich dune dynamics. In the two large-scale rivers, however, URANS is able to capture the origin and sustain migration of dunes over several months of simulated time.

The paper is organized as follows. First, we introduce briefly the hydrodynamic and morphodynamic models followed by the description of the experimental stream and virtual meandering rivers we used for simulations. Subsequently, we describe the experimental methods we employed to collect morphodynamic measurements in the OSL and present the simulation results for this case. This will be followed by the simulation results of macro-scale dunes in gravel and sand bed meandering rivers. Finally, we summarize main contribution of this work and discuss future extension of our work to simulate riverine systems during the full length of a flood hydrograph.