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Bedform dynamics from coupled bed-flow direct numerical simulations

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Abstract. We present results of time-evolving coupled direct numerical simulations between an erodible bed and an overlying pressure-driven, turbulent flow field. A total of 6 simulations are considered, the details of which are shown in Table 1. The numerical setup consists of a horizontally periodic open channel, and the simulations are run at a shear Reynolds number of $Re_\tau = 180$. The coupling between the spatially and temporally evolving sediment bed and the flow field is enforced through the explicit immersed boundary method (IBM) of Uhlmann [1]. The flow field is fully resolved and is obtained by integrating the conservation of mass and momentum equations using a pseudo spectral code [2]. On the other hand, the sediment bed is modelled via the Exner equation [3]. Details about the numerical approach are available in [4-5].

1 Background

Ripples are examples of bedform patterns that result from the instability of an erodible bed of particles subjected to the shearing action of an overlying flow field [6]. The evolution of ripples has been well documented experimentally and numerically. Here we show using coupled, flow-bed simulations that we are able to capture the various stages of ripple formation observed in experimental flumes.

2 Results from direct numerical simulations

Fig. 1 shows a top view and an isometric view with iso-contours of the bed-normal tangential velocity gradient. These simulations evolve from an initially flat bed. At the start of the simulation, the flow corresponds to a fully developed, $Re_\tau = 180$ turbulent open channel flow over a flat bed. Shortly afterwards, longitudinal streaks are easily discerned (panel b). These are aligned predominantly with the flow direction with only a few aligned at an angle of about 45°. The Chevron features are next to emerge in panel c followed by the incipient crestlines in panel d. The incipient crestlines then coarsen and grow in amplitude to form straight and sinuous ripples (panels e and f). These ripples will continue

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to grow and develop (and are hence termed developing ripples) until they reach an equilibrium or fully developed stage.

Table 1. List of simulations. Particle and fluid densities are held constant at 1.57 and 1.015 g/cm^3, respectively. Re_p is the particle Reynolds number. Θ_{cr} is the critical Shields number and Θ is the Shields number imposed by the flow. u_τ and H_f are the bed shear velocity and flow depth.

Simulation number	Particle diameter (µm)	Re_p	Θ_{cr}	Θ	u_τ (cm/s)	H_f (cm)
S1	250	9.347	0.029	0.109	1.237	1.455
S2	150	4.344	0.046	0.182	1.237	1.455
S3	50	0.836	0.122	0.547	1.237	1.455
S4	250	9.347	0.029	0.055	0.874	2.058
S5	150	4.344	0.046	0.091	0.874	2.058
S6	50	0.836	0.122	0.274	0.874	2.058

There is a rich spectrum of bedform interactions that occur during the development of the bed. [7] provide a thorough summary of the various bedform interactions documented in laboratory experiments as well as field studies. Some of these interactions may be constructive such as lateral linking and merging, which result in fewer, larger, and more widely spaced bedforms, or regenerative such as bedform splitting and defect creation, which push the system in the opposite direction towards a more preliminary state. Other interactions such as bedform and defect repulsion do not fall under the above two categories, but rather lead to bedform rearrangement through a pattern change.

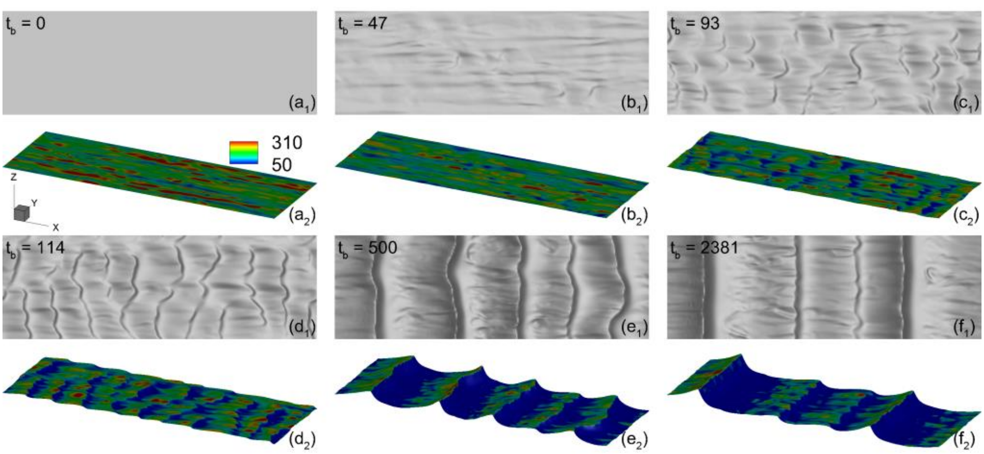

Fig. 1. Top (grayscale) and isometric (colored) views of the temporal evolution of the bed from S2 at six time instances. For each snapshot, the bed is shown in two different views. Flow is from left to right. The contours in the isometric view correspond to the bed-normal tangential velocity gradient.

In our simulations, we observe many such documented interactions including lateral linking, defect and bedform repulsion, defect creation, as well as merging. These interactions are present in all our simulations, but in the interest of brevity, we will show a single example of some of these interactions. In Fig. 2, we show a top view of the bed in which, for the purpose of clarity, bedform features are exaggerated by stretching the vertical direction by a factor of 4. Except for frames a_1 and a_2, we show iso-contours of the sediment bed height. Frames a_1-a_3 show the bedform interaction of lateral linking.

In frames b, c, and d, we observe various flow-aligned bedform interactions known as defect repulsion, bedform repulsion, and merging, respectively. The mechanisms behind all these bedform interactions are discussed in detail in [4].

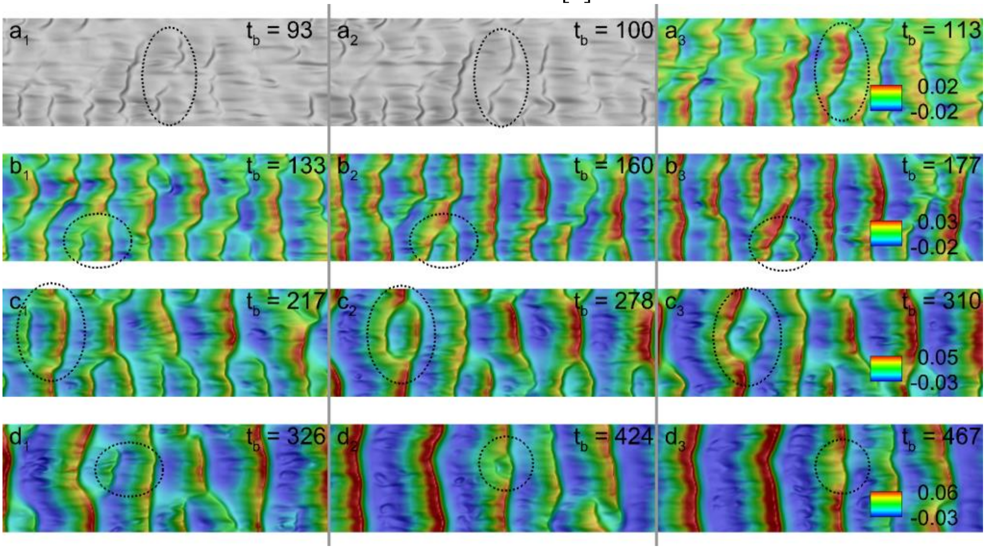

Fig. 2. Bedform interactions. See text for detail. The grayscale in the a panels is used for clarity.

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