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Modeling bedform development under turbulent flows using Large-Eddy-Simulation and Immersed-Boundary-Method

YQ. Nguyen *, J.C. Wells

Graduate School of Science and Engineering, Ritsumeikan University, 1-1-1 Nojihigashi, Kusatsu, Shiga, Japan

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ABSTRACT

A numerical model was built to study the mechanism of sedimentary bedform development in hydraulically smooth turbulent flows. The model consisted of a module for flows, a module for sediment transport, and a module for bed surface evolution. The flow was unsteady, three-dimensional and modeled by a Large-Eddy-Simulation (LES) method coupled with an Immersed-Boundary-Method (IBM). Governing equations were discretized on a fixed Cartesian grid by Finite Difference Method. Sediment (bedload) transport was estimated by Van Rijn formula corresponding to bed shear stress distribution obtained from the flow solution. The bed surface evolution was adapted to the sediment flux and described by the Exner–Polya equation. Updated bed surface was then used as the boundary for solving the flow field in the next time step. Time-advancement was discretized by the Adams–Bashforth method. The model was first validated by two test cases of bed shear stress and turbulence statistics over fixed sinusoidal bed surfaces. It was then employed to study initiation and development of bedforms from an initially flat bed to fully developed forms. Formation of newly and successively formed bedforms, growing and downstream propagating process of existing bedforms were very close to experimental observations. Instantaneous bed shear stress and corresponding sediment flux around evolving bedforms, which were difficult to observe in experiments, were also well produced by this model.

1. Introduction

In hydraulics, sediment transport and sedimentary bedform are of fundamental problems. They are known to strongly affect dynamics of rivers, such as erosion and deposition of river bed and banks, as well as transport capacity of the flow. Particularly, the bedform increases flow resistance, hence, influences living environment of aquatic creatures and enhances hydraulic disasters, such as draughts or floods.

The bedform developing in hydraulically smooth turbulent flow is named *ripple* whose development and mature dimensions are independent of the flow depth [1–4]. Ripple is observed to be initiated from small local disturbances on an initially flat bed [4–7]. The disturbances are about a few grain diameters [6,7] and formed by random pile-ups of the sediment on the bed [6] or by random actions of high turbulent velocities [7,8]. They continue to grow as more sediment is trapped, quickly become two-dimensional and disturb the flow field [6,7]. As a result, downstream bed shear stress distribution is caused to deviate from standard values in a region about 1–100 the disturbance height [4,7]. Bed surface is then deformed accordingly and the first sand wave appears on the bed surface. The wave continues to grow as more sediment is deposited at its downstream side and, at a critical height, a flow separation becomes visible. Successive waves appear one by one downstream and form a *ripple train* [7].

While growing, the sandwaves are propagating downstream at speed inversely proportional to their heights [2]. This yields the ‘coalescence’ process where the stronger and faster sand waves overtake the weaker ones [2,7,9]. After the coalescence process, existing system may be two- or three-dimensional depending on the applied shear stress compared to the critical one [9]. At higher bed shear stress, the sandwaves are more two-dimensional.

A coalesced wave is observed to keep growing until it reaches a mature dimension at which the sandwave simply propagates downstream without growing further [2,3,9]. In hydraulically smooth turbulent flows with the particle Reynolds number, defined based on the grain diameter and friction velocity, less than 2.5, the ripple length is about from 700 wall units to 2500 wall units [2,3] while the model ripple height is about 38 wall units [10].

There have been many attempts to study the process of bedform development numerically. However, just few of them focused

* Corresponding author at: Dept. of Civ. Eng., HCMC University of Technology, Viet Nam.

E-mail addresses: nguyenquocy@hcmut.edu.vn (YQ. Nguyen), jwells@se.ritsumei.ac.jp (J.C. Wells).

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on the hydraulically smooth region. Kennedy [11] is considered as the first one working on this subject with a two-dimensional potential flow over an erodible bed. Later, Richards [12] added viscous effects to the flow model with a one-dimensional turbulence model for flows in hydraulically rough regions. This work was then extended to the hydraulically smooth region by Sumer & Bakioglu [13,14] for analyzing ripple formations.

In this work, ripple development from an initially flat bed in a hydraulically smooth turbulent flow is modeled with a highly accurate solution for unsteady three-dimensional flows by Large-Eddy-Simulation (LES) method. Methods with Reynolds-Averaged Navier–Stokes equations (RANS) may be preferred in most engineering applications but in this case their performance is not satisfactory in solving flow separations behind the sandwaves which are critical to formation of the bedform [15–17], hence are not employed here. Direct-Numerical-Simulation (DNS) method can also be a good candidate, but requires more computational cost than LES [17].

In addition, as the sandwaves grow, the bed surface changes in time. A curvilinear body-fitted grid requires regridding, associating with interpolations of the flow field, over time. To facilitate this problem, Immersed-Boundary-Method (IBM) [18,19] is coupled into LES, hence bedforms are allowed to freely develop in a fixed Cartesian grid system.

In our previous short papers [20,21], we reported preliminary results of bedform development simulations obtained from the model. We used a preliminary version of the model to examine initiation of a bedform on an initially flat bed [20]. The model was then revised to be able to simulate bedforms up to mature state [21]. However, in those two papers, details of the model were not presented. In this paper, we add details of the model and discuss about its assumptions and limitations. More details of the equations and user-defined parameters, such as the maximum bed slope and the adaption length, as well as effects of their selected values on the results are presented. In addition, the validation tests have been revised for better matching of boundary conditions and for more grid resolutions. We also discuss more about effects of the flow separations behind the bedforms on their development and mature dimensions.

2. Numerical models

To build the computational model, the following assumptions were used, following suggestions in the literature.

- In hydraulically smooth flows, bed roughness and dynamics of individual grains have negligible effects on the flow field [3,4,13,14]. Therefore, in this study, the bed surface was treated as a *smooth*, continuum one.
- Effects of the free surface were ignored because development and mature dimensions of the bedform in the hydraulically smooth flows are independent of the flow depth and flow surface [1–3]. Accordingly, the free surface was treated as a fixed free-slip one.
- Only bedload was considered for sediment transport as it was observed to be dominant in the process of ripple formation [5,6,9,10].
- The local bedload flux does not adapt instantaneously to the local bed shear stress, hence there is a lag time, or equivalently, a lag distance between the two. This lag distance is shown to play a central role on formations of the sand waves [11,22].
- Time scale of flow development is much smaller than that of the bedform development [12]. Accordingly, bed surface was treated as a fixed one while hydrodynamic equations were being solved.

Based on the assumptions, a numerical model was built with the following components whose computational procedure is shown in Fig. 1:

- For the flow field: the unsteady, three-dimensional (3D) Navier–Stokes equation was solved with a Large-Eddy-Simulation (LES) method coupled with an Immersed-Boundary-Method (IBM).
- For sediment transport: the bedload formula proposed by Van Rijn [23], which is valid for low particle Reynolds numbers, was employed.
- For bed elevation evolution: the continuity equation, Exner–Polya formula [4] which relates the gradient of the bedload flux and time variation of the bed surface, was selected.

The sediment transport and bed elevation were evaluated in two-dimensional (2D) space. They were assumed to change in time and only in the longitudinal direction while homogeneous on the spanwise direction. A 2D model for the bed evolution facilitates the computational considerably, but should be sufficient to describe important characteristics of the bedform development process. It is reported that for very fine sands with very low particle Reynolds numbers and high bed shear stress, ripples are almost two-dimensional [2,9]. For the assumption of 2D bedforms to be validated in this model, the particle Reynolds number was assumed to be less than 1.0.

2.1. Module of hydrodynamic equations

The governing equations for LES coupled with IBM for viscous, incompressible fluids become [18,24]:

$$\frac{\partial \bar{u}_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + f_i \tag{2}$$

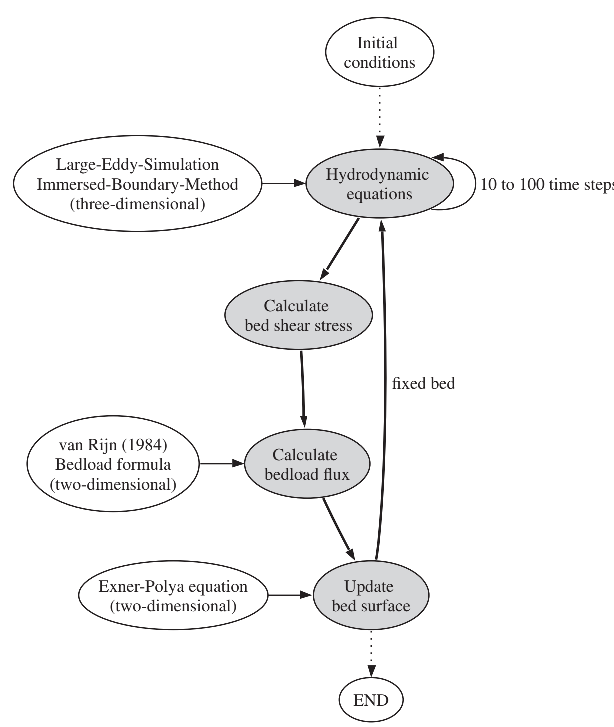

Fig. 1. Computational procedure.