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The effects of bed form roughness on total suspended load via the Lattice Boltzmann Method

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ABSTRACT

Bed forms in natural rivers and man-made channels provide the dominant contribution to overall flow resistance and hence significantly affect sediment transport rate. Many laboratory experiments and field observations have been conducted on bed forms, and it was found that theoretical flat-bed assumptions do not give the correct estimation for the total suspended load (TSL). In this study, we present a systematic numerical investigation of turbulent open-channel flows over bed forms using the Lattice Boltzmann Method (LBM). A static Smagorinsky model is incorporated into LBM to account for turbulence, and the dynamic interface between fluid and air is captured by a free-surface model. The time-averaged flow velocity, turbulence intensity and Reynolds shear stress in LBM simulations show an excellent agreement with the available experimental data. In addition, the coherent flow structures induced by the bed forms qualitatively agree with previous numerical results from Large Eddy Simulations based the Navier–Stokes equations. We then proceed to investigate the effects of bed form roughness, quantified by the total friction factor f_T, on sediment transport. It is found that the prediction of the TSL based on the theoretical flat-bed assumptions may lead to an overestimation of up to 30%, depending on the bed form roughness. In addition, the normalized TSL is linearly proportional to f_T and nearly inversely proportional to the ratio of downward settling velocity and upward turbulence induced diffusion. Our work proposes a general law linking these quantities to estimate the TSL, which has the potential for a more efficient and accurate engineering design of man-made channels and improved river management.

1. Introduction

Bed forms are present in nearly all fluvial channels and play an important role in dictating flow resistance, sediment transport and deposition. The presence of bed forms may alter the flow field and consequently affect the sediment transport in suspension. Generally, the strong wakes resulting from flow separation behind each bed form element will lead to an increase in the overall turbulence levels, and hence an extra turbulence induced diffusion that is able to enhance the flow capacity to carry sediments in suspension [1]. The increase of suspension concentration is one of the major sources of water pollutants which may harm the aquatic ecology [2]. Therefore, an in-depth study of the relationship between bed forms and sediments in suspension is of vital importance both in economy and in ecology.

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Notation

u, v	instantaneous flow velocities in x- and y-direction
$\bar{u}$, $\bar{v}$	time-averaged flow velocities in x- and y-direction
u', v'	velocity fluctuations in x- and y-direction
u_{sd}, v_{sd}	turbulence intensities in x- and y-direction
τ_{Re}	Reynolds shear stress $(-\rho\overline{u'v'})$
ρ	fluid density
C	sediment concentration
$\mathbf{u}_p$	velocity of the suspended sediments
$\boldsymbol{\varepsilon}$	diffusivity tensor of the sediments
w	settling velocity of the sediments
x, y	streamwise and wall-normal directions
$\boldsymbol{\varepsilon}^m$	momentum diffusivity tensor
γ	proportionality between $\boldsymbol{\varepsilon}$ and $\boldsymbol{\varepsilon}^m$
f_i	density distribution function in the ith direction
$\mathbf{x}$	position of the lattice cell
$\mathbf{c}_i$	lattice speed in the i-th direction
δ_t	time step
t	simulation time
τ_0	relaxation coefficient
f_i^{eq}	equilibrium density distribution function
$\mathbf{u}$	fluid velocity
p	fluid pressure
c_s	lattice speed of sound
Re	Reynolds number
L_{lu}	characteristic length in lattice units
U_{lu}	characteristic velocity in lattice units
ν_0	fluid kinematic viscosity in lattice units
ν_{total}	total fluid viscosity in lattice units
ν_{eddy}	turbulence eddy viscosity in lattice units
τ_{total}	effective relaxation time
C_s	Smagorinsky constant
Δ	filtered length of the Smagorinsky model
S	large eddy strain rate tensor
α, β	spatial indices
$\pi_{\alpha\beta}^{neq}$	sum of the second-order moments of the nonequilibrium f_i
Π	magnitude of the tensor $\pi_{\alpha\beta}^{neq}$
η	fluid fraction of a lattice cell
m	fluid mass inside a lattice cell
ρ_A	density of the gas phase
$\mathbf{n}$	surface normal vector
κ	small offset for cell type conversion
L	resolution of the cavity flow or the periodic length of the bed forms
U	velocity of the upper boundary in the cavity flow or mean flow velocity
h_w	height of the residual water column
x_w	advance of the collapsing water column
H_i, L_i	initial height and length of the water column
L_r, L_t	lengths of the recirculation region and the flume
L_e	distance between the entrance and the measured section
h	height of the bed form element
H	mean depth of the fluid flow
μ, σ	mean value and standard deviation
u_*	total shear velocity
Fr	Froude number
g	gravitational acceleration
S	slope of the inclined open channel
W	width of the open channel