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Gravity currents propagating over periodic arrays of blunt obstacles: Effect of the obstacle size

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ABSTRACT

Gravity currents are considered that propagate over a series of identical ribs with square cross sections. Both large-eddy simulations and a shallow-water approach are applied to assess the influence of rib height and Reynolds number. The simulations elucidate the physical mechanisms governing the time-dependent evolution of the drag force, which are dominated by the formation of a recirculation region immediately downstream of each rib, in conjunction with a supercritical, jet-like flow region above and behind the rib, and an upstream propagating hydraulic jump that forms as a result of the interaction between the gravity current and the neighboring rib immediately downstream. The corresponding shallow-water analysis yields fair agreement, indicating that simplified models can provide useful information for the present class of flows.

1. Introduction

The unsteady interaction of gravity and turbidity currents (Simpson, 1997; Meiburg and Kneller, 2010) with naturally occurring topography and/or engineering structures represents a multi-faceted flow problem, with applications ranging from submarine pipeline operation to powder-snow avalanche mitigation. Simplified models based on shallow-water theory have been proposed by various authors (Rottman et al., 1985; Lane-Serff et al., 1995; Gonzalez-Juez and Meiburg, 2009). Gonzalez-Juez et al. (2009a,b, 2010) were the first ones to employ highly resolved large-eddy simulations in order to investigate the interaction between a gravity current and an isolated obstacle. These authors were able to demonstrate good agreement with the experimental drag and lift force data of Ermanyuk and Gavrilov (2005a,b). Very recently, Tokyay et al. (under review) extended this line of simulation-based research to a periodic array of bluff obstacles. They showed that below a certain value of drag per unit streamwise length induced by the obstacles, the gravity current transitions to a slumping phase with a nearly constant average front velocity. For higher drag values, the slumping phase can be very short, and the flow begins to exhibit features familiar from gravity currents propagating through porous media (Tanino et al., 2005).

The present investigation focuses on the effects of obstacle size and Reynolds number in such situations, and it employs both large-eddy simulations as well as shallow-water theory. We consider the case of compositional Boussinesq currents in the full-depth, lock-exchange configuration, for which the height of the lock-gate opening is equal to the channel height H (Fig. 1). The initial volume of release is sufficiently large ($H/x_0 \ll 1$), so that we can neglect any interaction between the

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currents and the channel end walls. The current advances over a flat horizontal bed with an array of identical 2-D obstacles in the form of square ribs.

The next section will provide a brief overview of the governing equations and the computational approach. The flow structure will be discussed in Section 3, while Sections 4 and 5 will focus on the drag force. Section 6 presents the corresponding shallow-water analysis and Section 7 summarizes the conclusions to be drawn from the investigation.

2. Governing equations and numerical model

The time-filtered Navier–Stokes equations in the Boussinesq approximation and the advection–diffusion equation for the concentration are made dimensionless using the channel depth H and the buoyancy velocity, $u_b=\sqrt{g'H}$, where g' is the reduced gravity. Due to filtering, the governing equations for large-eddy simulations (LES) contain subgrid-scale stress (SGS) terms

$$\frac{\partial u_i}{\partial x_i}=0, \tag{1}$$

$$\frac{\partial u_i}{\partial t}+\frac{\partial u_i u_k}{\partial x_k}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_k}\left(\left(\frac{1}{\mathrm{Re}}+\nu_{SGS}\right)\left(\frac{\partial u_i}{\partial x_k}+\frac{\partial u_k}{\partial x_i}\right)\right)-C\delta_{i2}, \tag{2}$$

$$\frac{\partial C}{\partial t}+\frac{\partial C u_k}{\partial x_k}=\frac{\partial}{\partial x_k}\left(\left(\frac{1}{\mathrm{ReSc}}+\alpha_{SGS}\right)\frac{\partial C}{\partial x_k}\right). \tag{3}$$

Here p and u_i denote the time-filtered dimensionless pressure and the Cartesian velocity component in the i-direction, respectively. y (i=2) indicates the vertical direction. The time-filtered non-dimensional density, also referred to as the concentration, is $C=(\rho-\rho_0)/(\rho_1-\rho_0)$ where ρ_1 and ρ_0 are the densities of the lock and ambient fluid, respectively. Two dimensionless parameters appear in Eqs. (2) and (3), in the form of the Reynolds number ($\mathrm{Re}_b=u_bH/\nu$) and the Schmidt number $\mathrm{Sc}=\nu/\kappa$. The latter represents the ratio of the molecular viscosity, ν, to the molecular diffusivity, κ. The SGS viscosity and diffusivity are estimated using a dynamic model based on the resolved velocity and concentration fields (Pierce, 2001). The governing equations are integrated through the viscous sub-layer, which eliminates the need to use empirical near-wall corrections.

The time-filtered Navier–Stokes equations are integrated on a non-uniform Cartesian mesh via a finite-volume approach, with second order spatial and temporal accuracy. A semi-implicit iterative method that employs a staggered, conservative space-time discretization is used to advance the equations in time. A Poisson equation is solved for the pressure using a multigrid approach. The algorithm discretely conserves energy, which allows us to obtain solutions at high Reynolds numbers on relatively coarse meshes without adding artificial damping. All operators are discretized centrally, except for the convective term in the advection–diffusion equation, for which the quadratic upwind interpolation for convective kinematics (QUICK) scheme is used. Detailed validation of the code for 3-D LES simulations of intrusive lock-exchange gravity currents, and for gravity currents propagating over horizontal flat surfaces at Reynolds numbers up to 10^6 are discussed by Ooi et al. (2007, 2009). Comparisons with experiments investigating gravity currents interacting with isolated obstacles demonstrate that the simulations accurately reproduce the large-scale drag and lift forces (Gonzalez-Juez and Meiburg, 2009; Gonzalez-Juez et al., 2009a, 2010).

The top and bottom surfaces were simulated as no-slip smooth walls. The lock gate is positioned at the center of the channel (x/H=0). To maintain the symmetry in the evolution of the currents propagating over the bottom and top walls, the ribs are positioned along the bottom wall in the region with $x/H>0$ and along the top surface in the region with $x/H<0$. This set-up allows us to focus only on the evolution of the bottom propagating current.

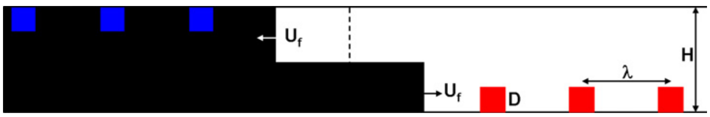

Fig. 1. Sketch of the computational domain in the lock-exchange flow simulations, with ribs placed along the top ($x/H<0$) and bottom ($x/H>0$) walls. The lock gate (dashed line) is situated at $x/H=0$. Initially, the area to the left of the gate holds fluid of higher density ρ_1, while the region to the right of the gate is occupied by fluid of the lower density ρ_0. Upon removal of the gate at time t=0, a gravity current forms.

Table 1
Main parameters of the simulations.

Case	Re	D/H	λ/H	Position of ribs
LR-R15	47,800	0.15	3	$x/H=\pm 5, 8, 11, 17$
HR-R15	10^6	0.15	3	$x/H=\pm 5, 8, 11, 17$
LR-R30	47,800	0.30	3	$x/H=\pm 7, 13, 19$