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Research paper

Reynolds number and settling velocity influence for finite-release particle-laden gravity currents in a basin

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A R T I C L E I N F O

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A B S T R A C T

Three-dimensional highly resolved Direct Numerical Simulations (DNS) of particle-laden gravity currents are presented for the lock-exchange problem in an original basin configuration, similar to delta formation in lakes. For this numerical study, we focus on gravity currents over a flat bed for which density differences are small enough for the Boussinesq approximation to be valid. The concentration of particles is described in an Eulerian fashion by using a transport equation combined with the incompressible Navier-Stokes equations, with the possibility of particles deposition but no erosion nor re-suspension. The focus of this study is on the influence of the Reynolds number and settling velocity on the development of the current which can freely evolve in the streamwise and spanwise direction. It is shown that the settling velocity has a strong influence on the spatial extent of the current, the sedimentation rate, the suspended mass and the shape of the lobe-and-cleft structures while the Reynolds number is mainly affecting the size and number of vortical structures at the front of the current, and the energy budget.

1. Introduction

Turbidity currents are particle-laden gravity-driven currents in which the gravitational driving force is supplied by a density excess associated with the suspension of particles. They exhibit a complex dynamic with the presence of the lobe-and-cleft patterns at the head of the current followed by a region of mixing with intense spanwise Kelvin-Helmholtz vortices. Understanding the physical mechanism associated with these currents as well as the correct prediction of their main features are of great importance for practical and theoretical purposes. This type of gravity-driven currents is the most important mechanism for the dispersal and deposition of sand on deep seafloors and on underwater slopes of many deltas and lakes. Their associated deposits can provide a valuable record of submarine landslide dynamics, shedding light on the magnitude of associated tsunamis, river flooding and major earthquakes (Talling et al. (2012)). They can also damage seriously seafloor cables and expensive seafloor installations for recovering oil and gas (Barley (1999)). More details about turbidity currents can be found in the extensive reviews of Meiburg and Kneller (2009) and Middleton (1993).

The deposits observed in nature are very complex, very voluminous and are extremely challenging and costly to study. As a result, turbidity currents have been mainly investigated in very simplified and idealized configurations. The most studied one is the horizontal channelized lock-exchange configuration in which uniformly suspended particle sediments are enclosed in a small reservoir separated by a gate from the fresh fluid. The dynamics of channelized currents is reasonably well understood with a large number of experimental, numerical and theoretical studies as well as predictive models (Middleton (1993); Meiburg and Kneller (2009)).

The first experimental investigations on non-channelized turbidity currents were reported in the 1950's by Kuenen (1951) with experimental studies of deposition patterns for turbidity currents in a basin configuration. Large-scale laboratory experiments, similar to the present configuration, are presented in Luthi (1981) to investigate the dilution process of the particles with the ambient fluid with a focus on the thickness of the deposit. In Bonnecaze et al. (1995), the authors studied experimentally axisymmetric gravity currents with a finite-release of particles to determine both the radius of an axisymmetric particle-laden gravity current as a function of time and its deposition pattern for a variety of initial particle concentrations, particle sizes, volumes and flow rates. More recently, Parsons et al. (2007) showed evidence of a mechanism called lobe switching (focusing of the flow into a single lobe) in their laboratory experiments for a basin configuration.

Highly resolved simulations of conservative gravity currents (with no suspended sediment) for non-channelized axisymmetric initial reservoirs

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were performed in Cantero et al. (2007b,a) for various Reynolds numbers. The objective was to address the structure and dynamics of cylindrical density currents and in particular to clarify the influence of circumferential stretching. The authors made some comparisons with a laboratory experiment for the case of saline water spreading in quiescent fresh water but with a much higher Schmidt number by comparison to the simulations. They found that their numerical simulations were in good agreement with experimental observations and with theoretical prediction models for axisymmetric currents (Hoult (1972); Huppert and Simpson (1980); Rottman and Simpson (1983); Ungarish (2009)).

Very recent high-fidelity simulations and laboratory experiments for circular and non-axisymmetric finite initial reservoirs (Zgheib et al. (2015a,c)) showed that the effect of an initial non-circular shape for the lock can persist for the whole duration of the observation, making most of prediction models irrelevant. The authors found that some of their non-axisymmetric currents eventually reach a self-similar shape with the same power-law spreading rate as an axisymmetric front. They also identified that the local speed of propagation is strongly dependent of the initial reservoir's shape, leading to local fast and slow fronts. They proposed an advanced box model, extending the classical box model (Huppert and Simpson (1980)), in order to account for the shape of the initial release (Zgheib et al. (2014, 2015b)). Theoretical and experimental tentatives to predict gravity currents in open basins was also made by Rocca et al. (2008, 2012). The authors used a complex model based on shallow-water theory for the prediction of the evolution of gravity currents. They found that currents in an open basin cannot be predicted using the usual framework adopted for channelized and axisymmetric gravity currents.

The main motivation behind the present numerical work is to study idealized gravity currents in an original basin configuration more representative of real situations than channelized and axisymmetric gravity currents. As a first step, we focus exclusively on the influence of the Reynolds number and settling velocity in the early stages of the evolution of the current. The paper is organized as follows. We first present the Direct Numerical Simulation (DNS) methodology, the flow configuration and the numerical parameters of each simulation. Some instantaneous visualizations followed by results about the spreading of the current, sedimentation rate, suspended mass and energy budget are discussed in the following sections. Then, the structure of the current at the wall and related deposition are discussed in great details. The paper is ended with a conclusion.

2. Numerical set-up

The flow configuration is shown in Fig. 1. Unlike axisymmetric lock-exchange configurations or the non-axisymmetric configuration of Zgheib et al. (2014, 2015b)), there is a preferential direction for the current, perpendicular to the initial reservoir (x_1-axis, streamwise direction). We assume a small volume fraction of the particles (typically less than 1%) so that interactions among the particles can be neglected as

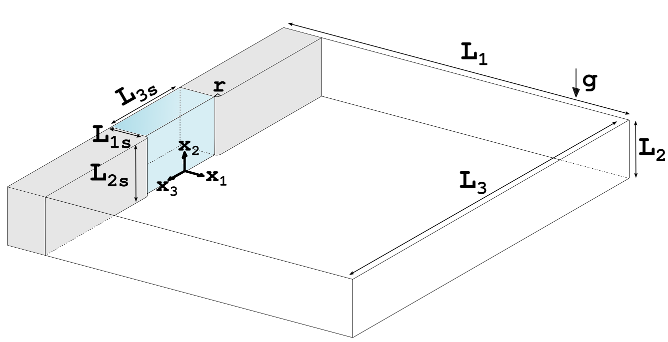

Fig. 1. Schematic view of the initial configuration of the lock-exchange open basin problem.

discussed in Espath et al. (2015). In this framework, the settling velocity u_s may be considered constant and is related to the particle diameter by the Stokes settling velocity law (Julien (2010)) which assumes that the dominant flow force on an individual particle is the Stokes drag. This flow configuration can be studied by solving the incompressible Navier-Stokes equations and a scalar transport equation under the Boussinesq approximation for the concentration of particles.

To make the equations dimensionless, half of the box height h and the buoyancy velocity u_b are chosen as the characteristics length and velocity scales, respectively. The buoyancy velocity is related to the reduced gravitational acceleration $u_b = \sqrt{g'h}$ where $g' = g\,(\rho_p - \rho_0)c_i/\rho_0$. Here, the particle and ambient fluid densities are ρ_p and ρ_0 respectively, with g defined as the gravitational acceleration, and c_i as the initial volume fraction of the particles in the lock. The Reynolds number is defined as $\mathrm{Re} = u_b h/\nu$ where ν is the kinematic viscosity, and the Schmidt number is defined as $Sc = \nu/\kappa = 1$, where κ is the mass diffusivity of the particle-fluid mixture. All other variables are made dimensionless using c_i, h or/and u_b. Thus, the incompressible Navier-Stokes equations and scalar transport equation can be written as

$$\frac{\partial \mathbf{u}}{\partial t} = -\nabla p - \frac{1}{2}[\nabla\cdot(\mathbf{u}\otimes\mathbf{u}) + (\mathbf{u}\cdot\nabla)\mathbf{u}] + \nu\nabla^2\mathbf{u} + ce^g + \mathbf{f} \quad (1)$$

$$\nabla\cdot\mathbf{u} = 0 \quad (2)$$

$$\frac{\partial c}{\partial t} + (\mathbf{u} + u_s\mathbf{e}^{\mathbf{g}})\cdot\nabla c = \kappa\nabla^2 c \quad (3)$$

where $\mathbf{u}$ ($\mathbf{x}$, t) is the velocity, p ($\mathbf{x}$, t) the pressure, c ($\mathbf{x}$, t) the particle concentration, $\mathbf{e}^{\mathbf{g}} = (0,-1,0)$ the unit vector in gravity direction and $\mathbf{f}$ is a forcing term to account for the basin geometry.

These equations are solved on a Cartesian mesh with the high-order flow solver Incompact3d[1] which is based on sixth-order compact schemes for spatial discretization and a third-order Adams-Bashforth scheme for time advancement. To treat the incompressibility condition, a fractional step method requires to solve a Poisson equation, fully solved in spectral space. With the help of the concept of modified wavenumber, the divergence free condition is ensured up to machine accuracy. The pressure mesh is staggered from the velocity mesh by half a mesh to avoid spurious pressure oscillations. The modelling of the channel-basin geometry is performed with a customized immersed boundary method based on a direct forcing approach that ensures a zero-velocity boundary condition at the wall of the solid geometry and a no-flux boundary condition for the particle concentration. Following the strategy of Parnaudeau et al. (2008), a mirror flow is imposed inside the geometry in order to avoid any discontinuities at the wall of the geometry. Note that the edges of the basin have been rounded ($r = 0.2$, as seen in Fig. 1). For the particles concentration, no-flux conditions are imposed at the wall of the geometry and are consistent with the boundary conditions of the computational domain. More details about the present code can be found in Laizet and Lamballais (2009). The size of the present simulations is such that we have no alternative but to use the parallel version of this solver (Laizet and Li (2011)), based on a highly scalable 2D decomposition library and a distributed FFT interface. **Incompact3d** has been extensively validated for axisymmetric gravity currents (non-published comparisons with the data from Zgheib et al. (2015c)) and for channelized gravity currents (Espath et al. (2014, 2015); de Rooij and Dalziel (2001)).

For the initial condition, a weak perturbation is introduced into the velocity field at the gate to mimic disturbances when the gate is removed. Free-slip boundary conditions are imposed for the velocity field in the streamwise and spanwise directions x_1 and x_3 while zero-velocity boundary conditions are used in the vertical direction x_2 (to mimic

[1] This open source code is available at www.incompact3d.com.