

THE DEVELOPMENT OF AN AXISYMMETRIC GRAVITY CURRENT

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Summary Three-dimensional releases of fixed volumes of saline fluids into fresh water and their radial spread have been examined experimentally. At high Reynolds numbers three distinct regimes have been identified. A short initial phase, a secondary phase where the frontal speed is constant and a final stage where the front speed is reduced. In the secondary stage the gravity current's head is dominated by the presence of a ring vortex above the front. This stage of the flow propagation comes to an abrupt end with the breakdown of the ring vortex at a clearly defined point. The experimental results have been compared to 2D and 3D numerical simulations. The simulations compare well with the experimental data for the early stages of the flow. The results show the development of a complex flow field and highlight the unsuitability of shallow water modelling for axisymmetric lock releases.

INTRODUCTION

Gravity currents have been studied extensively in different configurations because of their importance to a large number of industrial and environmental situations. An example of particular interest is the spread of a dense gas due to the rupture of a chemical storage tank. Understanding the dynamics of the gravity current arising after such an accidental release is crucial for a better risk assessment.

Previous work has revealed that gravity currents due to a fixed volume release into a parallel-sided channel behave differently from those allowed to spread radially. Numerical simulations of axisymmetric dam-break problems based on the shallow-water approximation were first presented by Rottman & Simpson (2) (3) for both the two-dimensional plane-flow case and the axisymmetric case discussed here. Solutions were obtained for the depth profiles of the dense fluid in both cases. In the axisymmetric case most of the heavy fluid appears to become concentrated in a ring between the front and a backward facing hydraulic jump behind the front that propagates from the centre: this jump propagates radially outward more rapidly than the front itself. Rottman & Simpson (2) proposed that the catch-up of the rear bore is the mechanism that is responsible for the formation of the frontal ring.

In this paper we examine the axisymmetric spreading gravity current in some detail, this study consists of laboratory experiments and numerical simulations.

METHODOLOGY

Three different types of laboratory experiment have been carried out in a sector-shaped tank 2.35 m long, with a sector angle measuring approximately 10° . In the first set of experiments the sector tank was filled with fresh water of density $\rho_A = 1000 \text{ kg/m}^3$ to a depth $H = 0.3 \text{ m}$. A fixed volume of denser fluid, density $\rho_L = 1013.5 \text{ kg/m}^3$, was kept behind a vertical barrier at a radial distance $R = R_0$ and at a depth h_0 , where $h_0 \leq H$, with fluid of density ρ_A above. By lifting the barrier the denser fluid is released into the widening part of the tank. For visualisation purposes the dense fluid was dyed with potassium permanganate. Illumination from behind using a diffuse light bank resulted in a sharply defined interface between the gravity current and the ambient fluid. The evolution of the resulting gravity current was recorded using a high resolution digital video camera with the movies saved to a computer. A mirror placed above the experiment allowed plan-view information of the gravity current's propagation to be recorded simultaneously using a single camera. The flow is characterised by the following parameters: the reduced gravity $g' = \Delta\rho g/\rho$, the fractional depth $\phi = h_0/H$, and the aspect ratio $\gamma = h_0/R_0$. In order to investigate the role of the fractional depth of the lock release on the front speed a number of experiments were carried out for different values of this parameter. In total four different experiments were carried out.

A second series of experiments to examine the effects of aspect ratio on a gravity current have also been carried out in this study. To create initial conditions that are as close to identical as possible the position of the lock gate, the reduced gravity g' , the heights H and h_0 have been kept constant. To vary the aspect ratio a barrier has been inserted into the lock at a distance R_1 from the centre, where $R_1 < R_0$. Data from these experiments has been obtained in exactly the same fashion as in the first set of experiments. The experiments have been analysed to investigate how variation of the aspect ratio γ effects the fronts propagation speed. The temporal evolution of the concentration field when γ is varied is also examined. In the third set of experiments a Particle Image Velocimetry (PIV) technique has been used to examine the temporal and spatial development of the gravity current's head. Pattern matching algorithms have been adapted for this purpose. For this set of experiments both the lock and the ambient fluid were seeded with a mixture of particles of differing densities. The flow was illuminated using a 5 mm vertical light sheet created using a 300 W arc lamp with a parabolic reflector to collimate the light. The use of a light sheet implies that three-dimensional movements could be filtered out as only the particles that remained in the light sheet are bright enough to be detected by the camera.

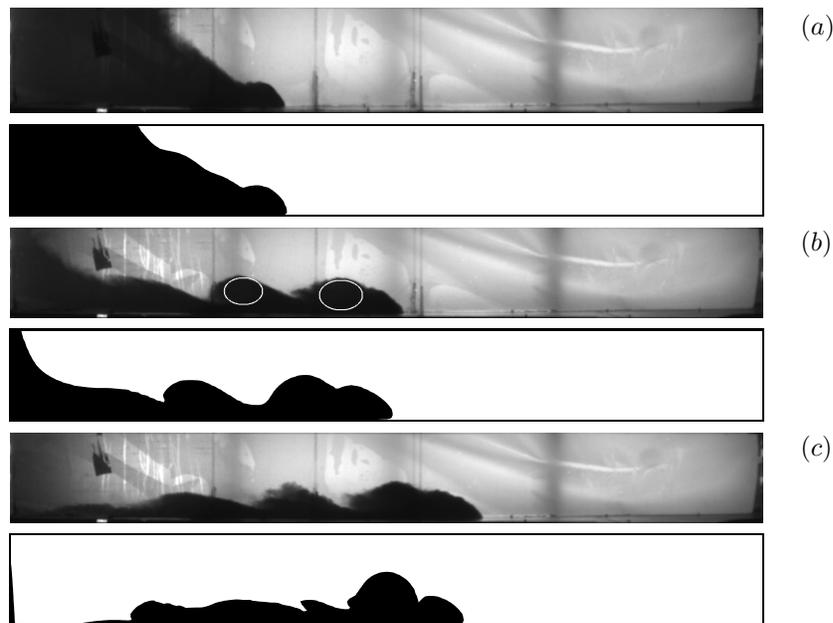


Figure 1. Experimental (upper picture) and numerical (lower picture) results showing the evolution the radially spreading gravity current for an axisymmetric lock release with $\phi = 1.0$, $g' = 13.2 \text{ cm/s}^2$ for times $t = 2.59 \text{ s}$ (a), 6.19 s (b), 8.70 s and (c).

Three-dimensional numerical flow simulations have been carried out with a code based on the Monotone Integrated Large Eddy Simulation (MILES) method described in Almgren *et al.* (1). The scheme is an incompressible variable density Navier-Stokes solver. The main difference between this MILES based code and other Navier-Stokes solvers is that there are no explicit closure schemes applied to solve for turbulence. The simulations are used to resolve the macroscopic scales in the problem and it is assumed that the flux-limiting monotone algorithms used for solving the set of coupled equations have a high frequency filter that inherently maintains physically reasonable behaviour near the grid scale cut-off.

RESULTS

The development of a full-depth gravity current $\phi = 1.0$, can be observed in figures 1 (a)-(c), which present experimental snapshots of the flow, together with the corresponding density plots from a two-dimensional axisymmetric numerical simulation. The figures clearly show a frontal bulge starting to develop shortly after the lock release (a). Then during the collapse of the dense fluid volume, vorticity is created mainly at the interface between the lighter and denser fluids. While being advected by the radially spreading fluid, the vorticity accumulates near the front, contributing to the formation of a gradually expanding leading ring vortex, a secondary ring vortex is also generated and the locations of the ring vortices are marked as white circles in (b). Vortex stretching appears to stabilise the rings (c) and these ring vortices become more intense. At a later stage the vortical flow can no longer be maintained and it vanishes abruptly. The front then continues to propagate outward without such a clearly defined structure. Comparison of the experimental and numerical results shows an excellent agreement for the initial stages of the flow (before vortex breakdown), with the front position and the form of the gravity current being accurately predicted.

Results from three-dimensional simulations have also been compared with two-dimensional numerical simulations.

References

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