Mixing in a Density-Driven Current Flowing over a Rough Bottom

C. Cenedese\textsuperscript{1}, R. Nokes\textsuperscript{2} and J. Hyatt\textsuperscript{3}

\textsuperscript{1}Department of Physical Oceanography
Woods Hole Oceanographic Institution, Woods Hole, 02543 MA, USA

\textsuperscript{2} Department of Civil and Natural Resources Engineering
University of Canterbury, Christchurch 8140, New Zealand

\textsuperscript{3} Department of Science and Mathematics
Massachusetts Maritime Academy, Buzzards Bay, MA 02532, USA

Abstract

Laboratory experiments have been conducted to investigate the mechanisms regulating mixing in a lock-release dense gravity current flowing over a bottom roughness represented by an array of cylinders. Both spacing (sparse vs. dense configuration) and height of the roughness elements compared with the height of the current have been varied. Experimental results suggest that enhanced mixing can occur via two different mechanisms. For a sparse configuration the dense current moves between the cylinders and the mixing is enhanced by the vortices generated in the wake of the cylindrical obstacles. For a dense configuration the dense current moves between the cylinders and the mixing is enhanced by the onset of convective instability between the dense current above the cylinders and the ambient lighter water between the cylinders. As expected, for small values of the cylinder height to the water depth, \(h/H\), the dense current behavior approaches that of a current over a smooth bottom, while the largest deviations from the smooth bottom case are observed for large values of \(h/H\).

Introduction

Gravity currents are generated by the difference in density between two fluids due to a difference in the temperature and/or the concentration fields. On Earth gravity currents occur both in the ocean, for example turbidity currents and overflows, and in the atmosphere, for example katabatic currents and sea breeze. For a review of gravity currents [16] provides an excellent overview.

Oceanographic overflows are dense water masses which often move over a sill or through a bathymetric constriction to then descend the continental slope until they reach their neutrally buoyant level or the ocean bottom. These dense masses are generally formed at high latitudes where the strong atmospheric cooling causes a temperature reduction, and the brine rejection, associated with the formation of ice, produces an increase in salinity.

The amount of mixing and entrainment occurring in dense oceanic overflows dictates their properties, and an accurate parameterization of this mixing in climate and general circulation models is of fundamental importance for a correct representation of deep water masses and the thermohaline circulation. The existing parameterizations for entrainment in dense currents account primarily for the shear-induced entrainment at the interface between the dense flow and the ambient fluid. However, the turbulence generated near bottom roughness can be intense and may influence the dynamics regulating mixing in dense overflows.

Oceanographic measurements through dense currents indicate that near the interface these currents typically have large turbulent displacements associated with a large velocity shear and a low Richardson number, indicative of shear-driven mixing [15]. Low Richardson numbers are also observed near the bottom of the dense currents due to the large shear caused by frictional drag.

Although entrainment and mixing processes in gravity currents propagating over a smooth bottom have been the subject of a large number of numerical, e.g. [8, 17, 13, 14], and laboratory, e.g [5, 4, 1], studies, very few investigations have focused on the entrainment and dilution generated by roughness elements at the bottom boundary. In particular, several improved parameterizations have been recently proposed for the entrainment due to shear-driven mixing [6, 17, 7, 2], but the inclusion of the dynamics arising in the presence of a bottom roughness is still missing in the widely used entrainment parameterizations.

Recently, studies investigating the closely related topic of fluid flow through aquatic canopies of various types have provided insights on the exchange flow, mean drag and propagation velocity of a dense current moving through a random array of vertical rigid cylinders. In particular, a surface gravity current propagating through a suspended canopy was investigated by [18]. An overview of the research in this area is given in [10].

Furthermore, [9] observed that the formation and collapsing mechanism of Kelvin-Helmholtz instabilities at the current interface was inhibited by bottom roughness, which may affect the entrainment into the current. Dense currents propagating over irregular rough beds (generated using sediments of different diameter) were investigated experimentally by [11] and the entrainment was observed to be enhanced (with the exception of the highest roughness) with increasing roughness (i.e., increasing sediment diameter).

This paper reports the results which are part of a larger study investigating the dynamics of lock-release gravity currents over rough bottoms. In particular, the focus is on the impact of different spacing between the roughness elements and different height of the elements on the dynamics regulating the gravity current behavior and the entrainment and dilution.

Methods

Experimental Apparatus

Experiments were conducted in a classical set up to generate a lock-release dense gravity currents. The tank was made of clear perspex to allow the flow to be visualized through the side walls, and it was \(L_T = 620\) cm long, \(H_T = 50\) cm high and \(W_T = 25\) cm wide with a flat bottom, as shown in figure 1. A stainless steel gate, sealed by plastic foam, was positioned 100 cm from one end of the tank. Hence the tank was divided into two regions, the lock filled with the dense fluid made of a 4 g/l salt.
solution, and the remainder of the tank filled with a lighter fluid made of a 5 g/l ethanol solution necessary to match the refractive index between the two fluids. The density of the two fluid was measured with an Anton Paar DMA5000 density meter and the reduced gravity was $g' = g(\rho_d - \rho_0)/\rho \approx 5 \text{ cm/s}^2$ for all experiments, where $\rho_d$ and $\rho_0$ are the density of the dense and ambient fluid, respectively.

Rigid plastic cylinders with a diameter of $d = 2 \text{ cm}$ and height that was varied between $h = 1, 2, \text{ or } 5 \text{ cm}$ were screwed into an aluminum base plate to generate the array of roughness elements located in the lighter fluid region for 300 cm behind the gate (figure 1). This set up allowed us to produce different roughness configurations by removing or adding cylinders on the aluminum base. In this paper we discuss the experiments having the two roughness configurations illustrated in figure 2 which we will refer to, hereafter, as the sparse and dense configurations. The distance between the centers of the cylinders was $\Delta S = 3.2 \text{ cm}$ and $6.4 \text{ cm}$ for the sparse and dense configurations, respectively. The denser fluid in the lock occupied the entire water depth (figure 1) which assumed values $H = 10, 15, 20, 27, \text{ or } 35 \text{ cm}$.

Non-dimensional Parameters

The non-dimensional parameters characterizing the bottom roughness are the plan density, $\sigma$, defined by

$$\sigma = \frac{A_P}{A_{TP}}, \quad (1)$$

where $A_P$ is the area of the base covered by the cylinders in plan and $A_{TP}$ is the total area of the base in plan; $\mu$, the elevation density, defined by

$$\mu = \frac{A_E}{A_{TE}}, \quad (2)$$

where $A_E$ is the area of the field covered by the cylinders in elevation as seen by the advancing current and $A_{TE}$ is the total area of the field in elevation (measured to the top of the cylinders); and $\alpha$, the aspect ratio, defined by

$$\alpha = \frac{h}{d}. \quad (3)$$

In the present experiments the above roughness parameters took the values of $\sigma = 0.35$ and $\mu = 0.62$ for the dense configuration and $\sigma = 0.35$ and $\mu = 0.62$ for the dense configuration. The value of $\alpha$ took the values 0.5, 1 and 2.5 for each configuration.

Finally, the non-dimensional number associated with the flow’s initial condition

$$\lambda = \frac{h}{H}, \quad (4)$$

which is the ratio of the cylinder height to the water depth. In the present experiments $\lambda$ varied between 0.03 and 0.5.

Density Field Measurements

The light attenuation (LA) technique [3] was used to determine the density field in each experiment. Multiple fluorescent bulbs were positioned behind the tank and illuminated the flow and a careful procedure was undertaken to make sure that the light intensity provided was constant during each experiment and dye calibration. The calibration of the tank and the dyed red salty solution was done by measuring the density and light attenuation for 8 different dye concentrations. The dyed solution was the same used to produce the dense fluid in the lock. The ratio of the average of blue and green/red intensity and a calibration curve based on Beer’s Law were used to calculate the densities fields during the experiments. The analysis of the images was done with the Streams software [12].

The experiments were recorded using a JAI BB141GE video camera with a zoom lens operating at 30.13Hz. The 1392x1040 pixel images were transferred directly to a fast hard drive on a PC during capture. To minimize the error due to parallax, an angled mirror was used to extend the light path that reached the camera. The image field or view of the camera was 50 cm wide and centered 100 cm downstream of the beginning of the roughness elements, at the lock gate.
The LA analysis produced non-dimensional 2D concentration fields translated into the frame of reference moving with the gravity current front. The variables were non-dimensionalised as follows:

\[ x' = \frac{x}{H} \quad \text{and} \quad y' = \frac{y}{H}, \quad (5) \]

and

\[ \rho' = \frac{\rho - \rho_0}{\rho_d - \rho_0}, \quad (6) \]

where \( x \) and \( y \) are the horizontal and vertical coordinates, respectively, where the origin of \( y \) is the flume bed and the origin of \( x \) is selected to be the location of the \( \rho' = 0.02 \) contour near the bottom.

Experimental Results

Figure 3 shows both the instantaneous non-dimensional density field (panels a and b) and the time averaged non-dimensional density field translated into the frame of reference moving with the gravity current front (panels c and d) for a gravity current propagating into a sparse (panels a and c) and dense (panels b and d) array of cylinders.

Experimental results suggest that two dynamically distinct mechanisms are in play when the current propagates through the sparse and dense array of cylinders. In the sparse configuration, the dense current propagates between the cylinders as clearly shown in figure 3d. This configuration is convectively unstable and dense fluid was observed to “free fall” between the cylinders and vigorously mix with the ambient lighter fluid. This mechanism enhanced the dilution of the dense current between and above the cylinders, as shown in the time averaged density field translated into the frame of reference moving with the front in figure 3d. As expected the dilution diminishes for decreasing values of \( \lambda \).

Figure 4 illustrates the time averaged non-dimensional vertical density profiles at a location one lock depth behind the nose of the current, i.e. \( x' = -1 \), for a sparse and a dense configuration for different values of the lock depth \( H \). As expected from the different dynamics observed in the sparse and dense configurations, the dilution of the current near the nose is in general larger for a current propagating in a dense configuration. In particular, in this configuration the dilution of the current between the elements is larger than in the current above for small values of \( \lambda \) and even for the smaller \( \lambda \) the current dilution is strongly enhanced compared to a current propagating over a smooth bottom (dashed line, figure 4) and into a sparse configuration. On the other hand, for decreasing values of \( \lambda \), the dilution of a current propagating into a sparse configuration decreases dramatically and for the smaller \( \lambda \) the vertical current density profile at \( x' = -1 \) is similar to that of a current propagating over a smooth bottom (figure 4a).

Conclusions

Laboratory experiments investigated the influence of bottom roughness on the dynamics regulating the entrainment and dilution of a lock-release dense gravity current. The configuration of the roughness elements, as well as their height and the height of the dense water in the lock were varied. Density fields were obtained using a light attenuation technique. The key results can be summarized as follow:

1. In a sparse configuration, the dense current is observed to propagate between the cylinders with a reduction in propagation speed. For currents having a height of the same order as the cylinders’ height the entrainment and mixing is enhanced by the vortices generated in the wake of the cylindrical obstacles. The configuration of the density fronts, as well as their height and the height of the dense water in the lock were varied. Density fields were obtained using a light attenuation technique. The key results can be summarized as follow:

2. In a dense configuration, the drag exerted by the cylinders does not allow the current to propagate between the cylinders and forces it to propagate on top of the roughness array. Hence, dense fluid is located on top of the lighter fluid between the cylinders.
cylinders, resulting in a configuration which is convectively unstable. Hence, the dense current dilution is highly enhanced for all values of $\lambda$.

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References


