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TECHNICAL DESIGN NOTE

Image analysis technique applied to lock-exchange gravity currents

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Abstract
An image analysis technique is used to estimate the two-dimensional instantaneous density field of unsteady gravity currents produced by full-depth lock-release of saline water. An experiment reproducing a gravity current was performed in a 3.0 m long, 0.20 m wide and 0.30 m deep Perspex flume with horizontal smooth bed and recorded with a 25 Hz CCD video camera under controlled light conditions. Using dye concentration as a tracer, a calibration procedure was established for each pixel in the image relating the amount of dye uniformly distributed in the tank and the greyscale values in the corresponding images. The results are evaluated and corrected by applying the mass conservation principle within the experimental tank. The procedure is a simple way to assess the time-varying density distribution within the gravity current, allowing the investigation of gravity current dynamics and mixing processes.

Keywords: density fields, gravity currents, image analysis technique, lock-exchange

1. Introduction

Gravity or density currents, driven by buoyancy differences between two contacting fluids, encompass a wide range of geophysical flows which can be originated by temperature, dissolved substances or particles in suspension. These may occur spontaneously in nature or as a result of human intervention. In the atmosphere, thunderstorm outflows and sea-breeze fronts are gravity currents driven by differences in temperature, whereas avalanches of airborne snow, plumes of pyroclasts from volcanic eruptions and sand storms are atmospheric flows where suspended particles play a major role in density gradients. In the water one may refer to oceanic fronts, resulting from differences in temperature and salinity, and turbidity currents caused by high concentration of suspended particles. Gravity currents are pertinent to engineering sciences, namely in what concerns industrial safety and environmental protection. The release of pollutant materials into rivers, oil spillage in the ocean and desalination plant outflows are a few examples of anthropogenic gravity currents, frequently with negative environmental impacts. The study of the dynamics of gravity currents, particularly mixing processes and entrainment, is still a topic of active research nowadays (Fernandez and Imberger 2006, Cenedese and Adduce 2008, La Rocca *et al* 2008, Thomas and Marino 2012, among others). Mixing between the current and the ambient fluid takes place throughout the current development, with the details of the density structure and of the concentration distribution of the mixed fluid being of central importance to understand, for instance, how mixing affects the evolution of the flow and to define the boundaries of influence of bed roughness on current kinematics. Closures to gravity

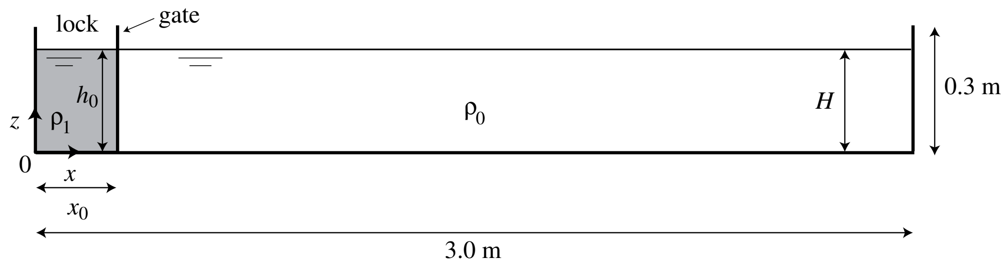

Figure 1. Schematic lateral view of the Perspex tank aimed at the lock-exchange experiments and definition of the coordinate system.

current models are still required to handle, for instance, bed heterogeneity in the case of high relative roughness and upper boundary temporal intermittency. The dynamics of both head and body of gravity currents is also an open subject needing further empirical evidence.

This note presents an image analysis technique based on light reflection through which instantaneous density fields of gravity currents are inferred. Gravity currents produced by lock-release of a fixed volume of saline water into a fresh water tank are captured by a 25 Hz CCD camera under controlled light conditions, using dye concentration as a tracer. Herein one single experiment, for a given initial density in the lock, is shown to illustrate the application of the experimental technique that allows reconstruction of the 2D time-varying density field in a density current. The technique herein presented is comparable, but nevertheless different to the techniques based on light absorption found in the literature (Hacker *et al* 1996, Thomas and Marino 2012), giving similar results regarding density distribution and kinematics of gravity currents.

The experimental setup is described in the following section followed by the description of the calibration procedure. Reconstructed density maps are then shown and commented upon and finally conclusions on the suitability of the experimental technique are drawn.

2. Facilities and experimental procedure

The lock-release experiment shown herein was performed, as in Adduce *et al* (2012), in a horizontal and rectangular cross-section tank 3.0 m long, 0.2 m wide and 0.3 m deep (figure 1) with smooth bed, $\varepsilon \approx 0$, and transparent Perspex walls at the Hydraulics Laboratory of University Roma Tre. The saline mixture with initial density $\rho_1 = 1014.7$ kg m^{-3} is placed in a lock with a vertical sliding gate at a distance $x_0 = 0.15$ m from the left wall of the tank. The right side of the tank is filled with fresh water with density $\rho_0 = 997.8$ kg m^{-3}, both sides filled up to same depth, i.e. $h_0/H = 1$, where $h_0 = 0.20$ m is the depth of the fluid in the lock and H is the total depth of the ambient fluid (cf figure 1).

Temperature measurements are performed in both fresh water in the tank and saline mixture in the lock. The densities of the saline mixture and of the ambient fluid are determined at the beginning of each run. A pycnometer is used to determine the density of the saline mixture, with the error of the weighing apparatus being 0.05%. A controlled quantity of white colourant (E171, titanium dioxide) is added to the mixture in the lock to provide flow visualization. High contrast between the current and its background is achieved through the placement of black paperboard in the back wall of the tank, producing a dark, uniform background. The experiment starts when the gate is suddenly removed and a density current starts to develop along the tank bed. The evolution of the gravity current is recorded by a CCD video camera with 768 × 576 pixels of resolution and acquisition frequency of 25 Hz. The camera is kept at a fixed perpendicular position 5.8 m from the tank and aligned with its centre to capture the whole tank length. The illumination is made by means of ambient artificial fluorescent light. During the experiments, the upper part of the tank is covered with a thin black painted wooden board to avoid reflection of light from the water surface. The captured video frames are subsequently converted into greyscale matrices in the region of the tank with fluid (702 × 43 pixels) and then converted into instantaneous density fields of the current through a calibration procedure.

3. Calibration method

The evaluation of the current density distribution is based on a relation between reflected light intensity and concentration of dye present in the flow; the latter is considered linearly correlated with salt concentration within the current body. A calibration procedure was carried out for each single pixel in the region defined earlier (702 × 43 = 30186 calibration curves, in the present case) to establish the relation between the amount of dye in the water and the values of greyscale in the frames representing light intensities. A pixel-by-pixel calibration avoids the errors induced by assuming uniform light and background conditions in the region of analysis. Eight known dye quantities, increasingly from zero to a maximum value corresponding to ρ_1, were uniformly distributed through the tank, the corresponding images being captured for calibration for the very same light conditions and distance between camera and tank as during the experiments. Assuming a direct relation between the amount of dye and density of the current, it is thus possible to infer density values at any given pixel and at any given instant from its instantaneous greyscale value. A cubic interpolation applied to each pixel individual calibration curve allows the conversion, in a continuous way, of the greyscale values into density. Figure 2 shows a calibration curve for one single pixel in the centre of the image, whose location is illustrated with a white dot in the presented frames, where greyscale values increase nonlinearly with the amount of dye in the flow.

Figure 2. Example of images used for calibration and the corresponding calibration curve. The reference point corresponds to one central pixel of the image and is represented in the frames by white dots.

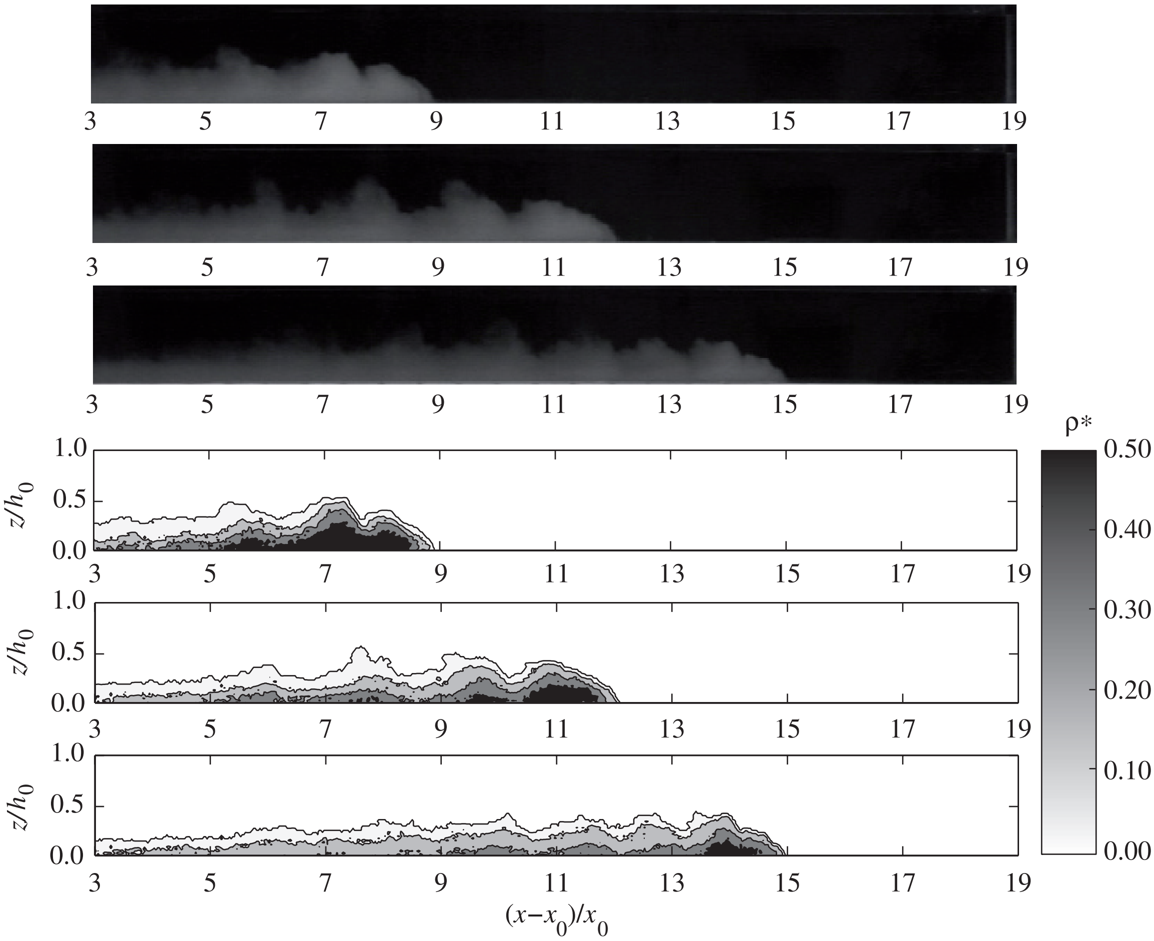

Figure 3. (top) Photos of the current acquired at $t = 20$, 28 and 36 s after the gate removal; (bottom) corresponding non-dimensional isodensity contours plotted at $\rho^* = 0.02$, 0.15, 0.30 and 0.50.

Oscillations in the intensity of the ambient light were detected when analysing the temporal series of greyscale values in each pixel of a selected region in the acquired frames. Both 'dark' (low greyscale values) and 'white' (high greyscale values) regions were analysed and the deviations from the temporal mean of greyscale values were compared, in each pixel. Average deviations are higher in 'dark' regions (8%), which corresponds to a deviation of 0.5% in terms of density. 'White' regions show lower average deviations from the mean (1.3%) but in terms of density the deviation is more relevant (6%), once the calibration curves (figure 2) are of exponential type, in which density grows with the increase of greyscale values. These deviations are overall corrected when applying the mass conservation principle to the entire experimental tank, thus accounting for the current mass and the mass of ambient fluid. This correction covers overall experimental and data treatment errors and it proves to be of the order of magnitude of 0.1%, i.e. the relative deviation between the total mass in the tank, considering the amount of water (m_0) and salt (m_s) introduced in the tank at the beginning of the experiment ($m_s + m_0$), and the total mass evaluated experimentally ($w(\int_{V_{c(t)}} \rho(x, z, t)\, \mathrm{d}V + \int_{V_{0(t)}} \rho_0\, \mathrm{d}V)$), where w is the width of the tank, $\rho(x, z, t)$ is the local density of the current, with t being the time after gate removal, V_c and V_0

volumes of the gravity current and the ambient fluid per unit width of the tank, respectively, and V volume considered per unit width of the tank.

4. Density maps

Figure 3 shows the development of the current captured at instants t = 20, 28 and 36 s after the gate removal and the corresponding reconstructed non-dimensional instantaneous isodensity contours plotted for 0.02, 0.15, 0.30 and 0.50, the non-dimensional density being defined as $\rho^*(x, z, t) = (\rho(x, z, t) - \rho_0)/(\rho_1 - \rho_0)$, where $\rho(x, z, t)$ is the local density of the current.

A preliminary assessment of the density fields shows that mixing processes are not confined to the boundary between current and ambient fluid, rather they extend through the entire depth of the current. Figure 3 shows that the head is the region where higher density is observed, which is in accordance with previous observations (Hacker *et al* 1996, Hallworth *et al* 1996, Marino *et al* 2005). Regarding gravity current kinematics, results from the performed experiments can be consulted in Nogueira *et al* (2013), which are comparable to previous observations in currents with similar characteristics (Rottman and Simpson 1983, Marino *et al* 2005, Adduce *et al* 2012), regarding the evolution of the current front position and velocity and the transition between first and second phases of the current development. Furthermore, the analysis of the temporal evolution of the dimensions and mass of the head of these currents shows interesting cycles of head stretching and breaking throughout the gravity current development (Nogueira *et al* 2012), the breaking events being followed by the formation of large-scale billow structures at the rear of the gravity current head, which eventually fade in time by diffusion-type processes. This is visible in figure 3, following the evolution of the billow structure at positions $(x - x_0)/x_0 =$ 7.0, 8.0 and 8.5 (at $t = 20$, 28 and 36 s, respectively).

Ongoing work on entrainment assessment in unsteady gravity currents, taking the mass growth rate at the gravity current head as a measure to locally estimate entrainment, shows that this phenomenon occurs at all stages of the current development. Results (not shown here) indicate that the entrainment parameter estimated in a bulk fashion for the entire current is comparable to previous results from steady gravity currents, our results being particularly well fitted by the entrainment law of Parker *et al* (1987).

5. Conclusions

The image analysis technique presented herein is a simple method based on light reflection to assess the instantaneous density fields of gravity currents. The calibration procedure and density estimation are obtained for each individual pixel in the image of analysis, the results from this procedure being verified through the total salt mass conservation principle applied to the entire experimental tank. Density evaluation errors on individual pixels are below 8%. The relative deviation between the total mass in the tank and the total mass evaluated experimentally, of the order of magnitude of 0.1%, is then corrected covering overall experimental and data treatment errors. The resulting density maps are useful data for the ongoing investigation of the current kinematics, namely current front position and velocity and current dynamics and mixing processes, particularly the entrainment of ambient fluid into the current.

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