DYNAMICS OF THE HEAD OF GRAVITY CURRENTS

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Abstract: Gravity currents, from which turbidity currents are an example, occur in reservoirs and lakes with potential hazards on what concerns sedimentation and water quality issues. The dynamics of gravity currents produced by full-depth lock-release of saline water into a fresh water tank are herein investigated. More specifically, the present results concern to the head of gravity currents where main interaction with the ambient fluid is observed. The experiments were conducted in a 3.0 m long Perspex flume of horizontal bed and rectangular cross section of 0.20 x 0.30 m^2 and recorded with a 25 Hz CCD video camera. An image analysis technique is used to evaluate time-space varying density distribution of unsteady density currents. The identification of the current head, based on the local vertically-averaged mass of the current, allows the characterization of its length and mass, both varying in time and space. Temporal evolution of these parameters show repeated cycles of stretching and breaking, where mass detachment from the head towards upstream, within the current body, is observed. This feature is related with instabilities signatures observed in the boundary region between current and ambient fluid and help to understand the entrainment phenomenon at the current head.

Keywords: gravity currents, image analysis, mass transfer.

INTRODUCTION

Gravity or density currents encompass a wide range of flows driven by density differences which can be originated by temperature, dissolved substances or particles in suspension and several examples of gravity currents in the nature can be found in Simpson (1997). This kind of currents may occur spontaneously in nature or as a result of human intervention. In the atmosphere, thunderstorms outflows and sea-breeze fronts are density currents where the difference in temperature plays a major role, while avalanches of airborne snow, plumes of pyroclasts from volcanic eruptions and sand storms are atmospheric flows driven by suspended particles. The releases of pollutant materials into rivers, oil spillage on the sea and desalination plant outflows are a few examples of man-made density currents that occur in the water masses and frequently cause negative environmental impacts. The loss of storage in reservoirs, related to the deposition of fine sediments due to turbidity currents, is a subject of great concern to hydraulic engineers and still a topic of research nowadays (Rossato and Alves 2011, Alves et al. 2008); several practical measures have been applied over the years to control sedimentation within reservoirs (Fan and Morris 1992, Kantoush et al. 2010) and innovative solutions are still being investigated (Oehy and Schleiss 2007). Therefore, the understanding of the mechanisms underlying this phenomenon, especially on what concerns mass transfer between the current and ambient fluid, is of extreme importance for the development of prevention measures against its eventual adverse effects.

In the last 30 years advances have been made on the analysis of the physics of density currents, both by using experimental (Rottman and Simpson 1983, Marino et al. 2005) and numerical modelling (Härtel et al. 2000, Ooi et al. 2007, Paik et al. 2009; Bombardelli et al. 2009). Several studies have been developed through image analysis technique to investigate the dynamics of gravity currents (Adduce et al. 2009, La Rocca et al. 2008); the present research, based on experimental work, uses similar techniques (Nogueira et al. 2011).

The aim of the present work is to experimentally investigate the dynamics of the head region of gravity currents performed by lock-exchange releases of saline water into a fresh water tank. Eight different lock-exchange tests were performed varying the initial density of the saline water, the water depth and bed roughness. Herein we present the results for only one experiment for a density current, with initial density of the saline mixture $\rho_1 = 1015$ kgm^{-3}, water depth h_0 = 0.20 m and flowing over a horizontal smooth bed, where stretching and breaking cycles and clearly observed in the current head.

EXPERIMENTAL DETAILS

The experiments were carried out at the Hydraulics Laboratory of University of Rome, “Roma Tre”, in a 3.0 m long transparent Perspex channel with a 0.2 m wide and 0.3 m deep rectangular cross-section (Fig. 1).

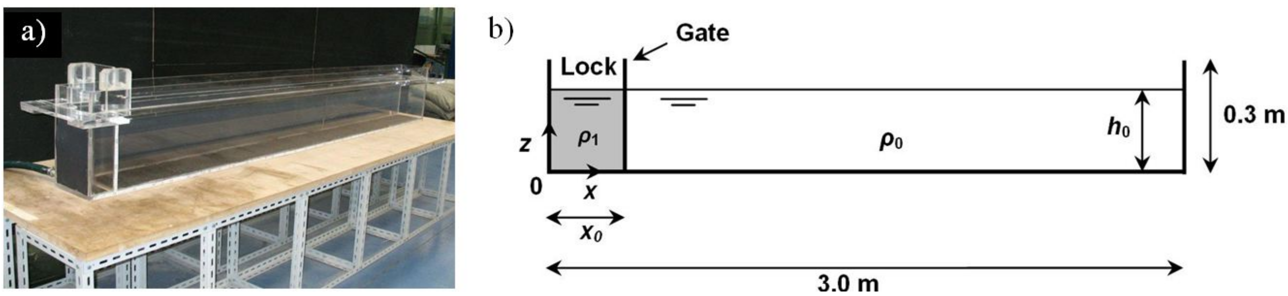

Fig.1 – Perspex channel: a) perspective photo and b) longitudinal view

A vertical sliding gate is placed in the channel at a distance x_0 = 0.15 m from the left wall to form a lock. The right side of the channel is filled with fresh water with density ρ_0, whereas the lock is filled with saline water with density ρ_1; both sides filled up at same depth, h_0 = 0.20 m. The channel bed is smooth (Perspex roughness $\varepsilon \approx 0$ mm) and horizontal. The density of the saline water is controlled by a pycnometer being the error of the weighing apparatus 0.05%. A controlled quantity of white colorant is added to the mixture in the lock to provide flow visualization. The outside back wall of the channel is lined with black paperboard to produce a dark, uniform background to contrast with the white dyed developing gravity current. At the beginning of each experiment the gate is suddenly removed, leaving the dense fluid to flow under the fresh water.

The evolution of the gravity current is recorded by a CCD video camera with 768 x 576 pixels of resolution and acquisition frequency of 25 Hz. The camera is kept at a fixed perpendicular position 5.8 m from the channel and aligned with its centre to capture the entire channel length. A metric scale is positioned in both horizontal and vertical directions of the channel for geometric calibration purposes. The illumination is made by means of artificial light. During the experiments, the upper part of the channel is covered with a thin black painted wooden board to avoid reflection of light from the water surface. The video frames were subsequently converted into gray scale matrices in the region of the channel with fluid (702 x 43 pixels) and then converted into instantaneous density fields of the current through a calibration procedure.

Eight known dye quantities, increasingly from zero to a maximum value corresponding to ρ_1, were uniformly distributed through the channel being the corresponding images captured for calibration for the very same light conditions and distance between camera and channel as during the experiments. Gray scale values increase nonlinearly with the amount of dye in the flow. Assuming a direct relation between the amount of dye and the density of the current (the dye introduces a negligible extra-density to the fluid of about 0.2%), it is thus possible to infer density values at any given pixel and at any given instant from its instantaneous gray scale value. The results from this procedure are then verified and eventually corrected through total salt mass conservation principle applied to the entire experimental channel, accounting thus with the current mass and the mass of ambient fluid.

Fig. 2 shows the development of the current captured in three instants (t = 20, 28 and 36 s) after the gate removal and the correspondent plot of iso-density contours plotted for ρ^* = 0.01, 0.15 0.30 and 0.50, being ρ^* the instantaneous 2D local non-dimensional density defined as

$$\rho^* = \frac{\rho(x,z,t) - \rho_0}{\rho_1 - \rho_0} \tag{1}$$

where $\rho(x,z,t)$ is the local density of the current.

In Fig. 2, the vertical Cartesian coordinate is normalized by the total flow depth h_0 whereas time is normalized by lock length x_0 and buoyancy velocity, given by $u_b = \sqrt{g' h_0}$, and g’ is the reduced gravity $g' = g\left(\rho_1 - \rho_0\right)/\rho_0$.

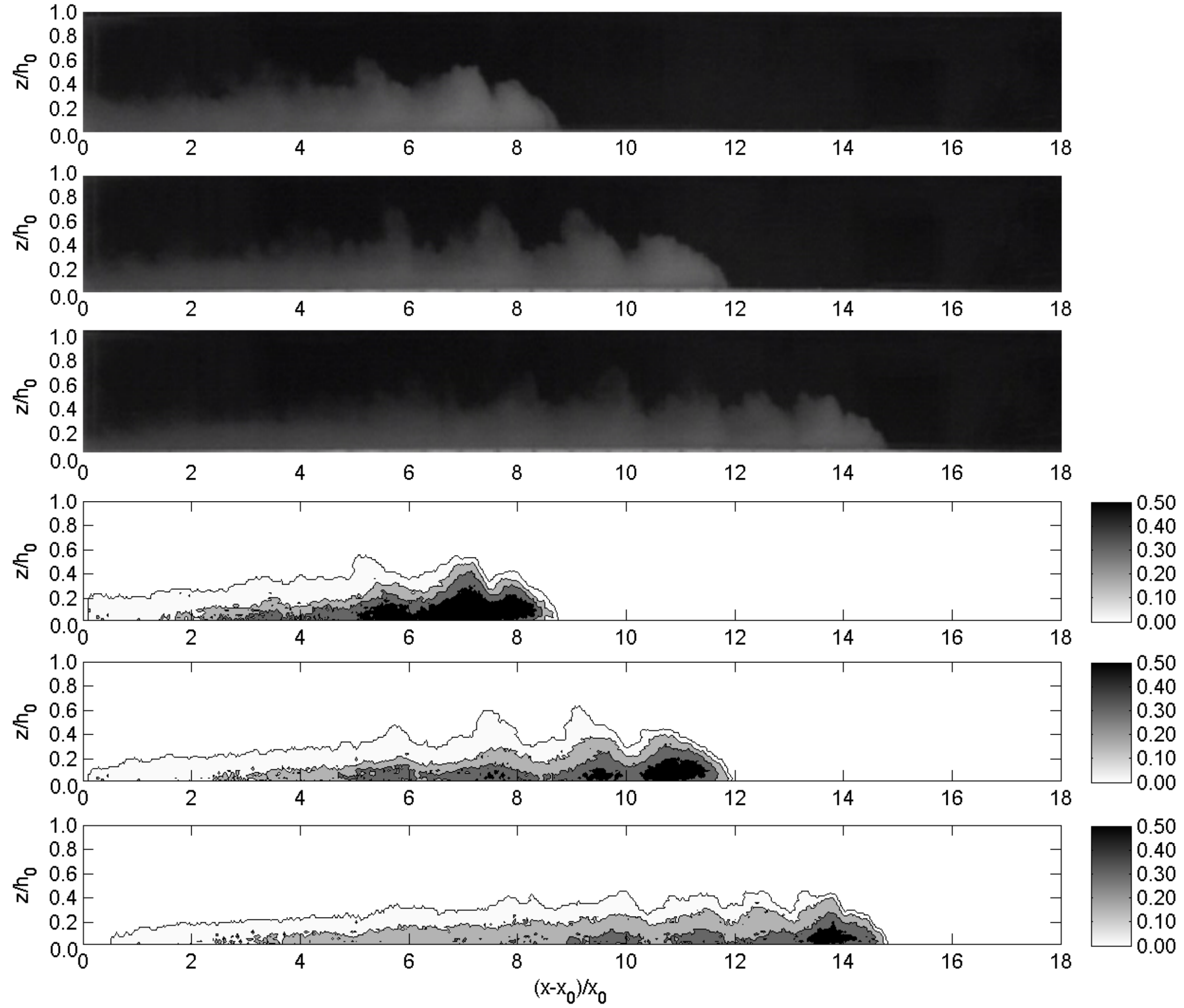

Fig. 2 – Photos (top) of the current acquired at t = 20, 28 and 36 s (tu_b/x_0 = 22, 32 and 41, respectively) after the gate removal and corresponding density fields (bottom). Iso-density contours plotted at $\rho^* = 0.01$, 0.15, 0.30 and 0.50

RESULTS

Since the head of the density current is the region where higher density is observed, the criterion used to characterize and isolate this region was based on a dynamic function given by the product between local values of depth-averaged density and current height:

$$W(x,t) = \overline{\rho_v}(x,t) \cdot h(x,t) \tag{2}$$

which corresponds to local vertically-averaged mass of the current (kgm^{-2}). The upstream limit of the head, and therefore the head length L_f, was defined taking the position of the meaningful local minimum of function W nearer the current front. Accordingly, Fig. 3 illustrates the definition of the head of the gravity current.

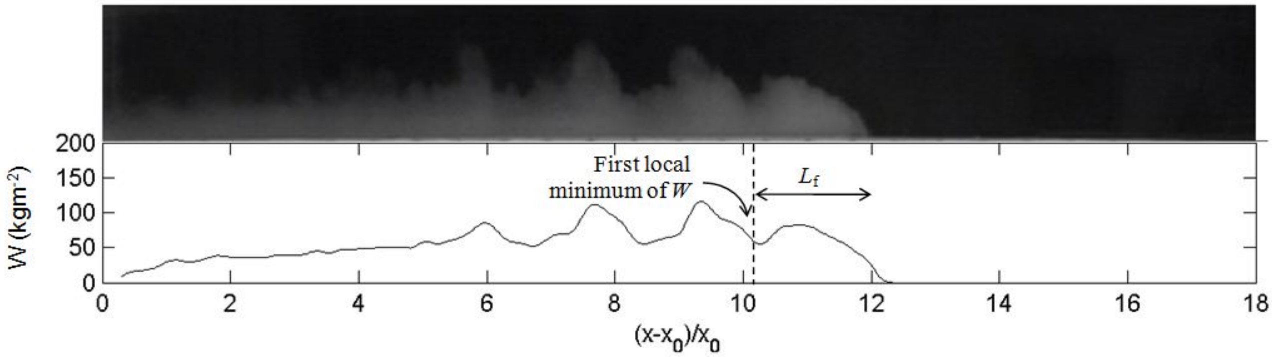

Fig. 3 – Definition of the density current head

The head of the current constitutes the control volume herein analysed. The estimation of head mass can thus be made through integration of the concentration values measured within this.

Fig.4 shows the main results regarding head dynamics, namely the temporal evolution of the head length and head mass, m_f (both normalized, by x_0, the lock length, and m_0, the initial mass in the lock, respectively)

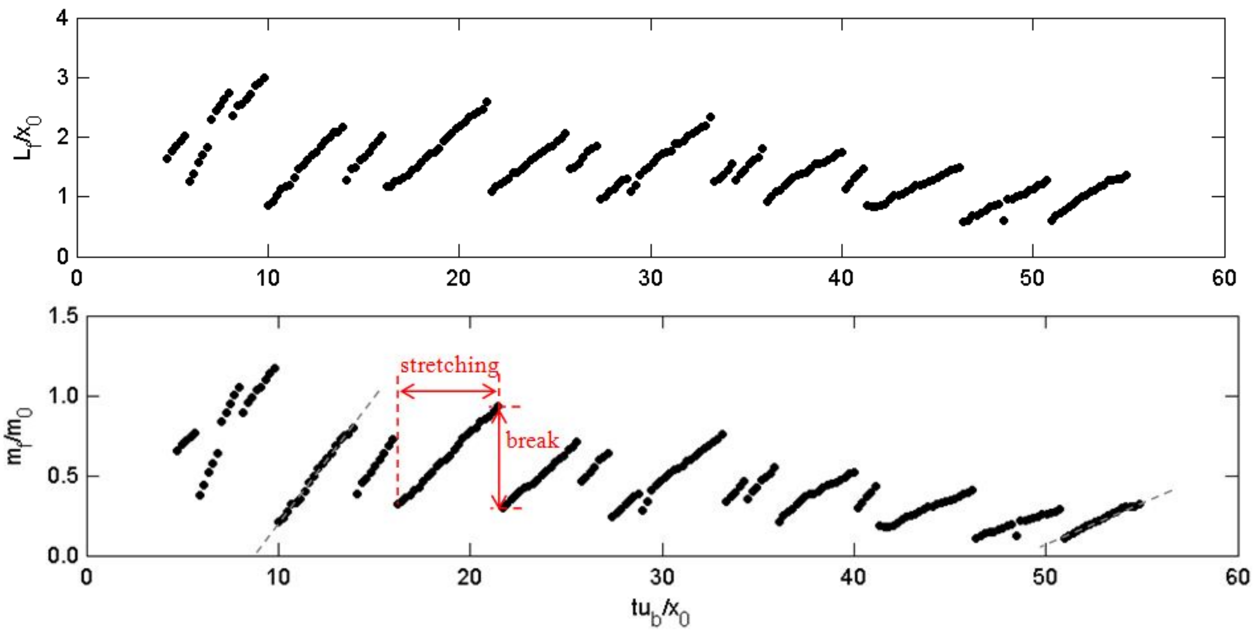

Fig. 4 – Head length (top) and mass of the head (bottom)

DISCUSSION

As the current advances, the front dynamics is characterized by repeated cycles of stretching and breaking (Fig. 4), where mass detachment from the head towards upstream, into the current body, is observed. The stretching phase is characterized by an increase both in length and mass of the head due to entrainment of ambient fluid into this region, the slope of each stretching event corresponding thus to the growing rate of mass at the current head. In the first moments of the current development, the entrainment of ambient fluid into the head (stretching phase) causes head mass values with the order of magnitude of the initial mass in the lock, thus, high concentration of mass in the current front is observed. Fig. 4 (dashed lines starting at tu_b/x_0 = 10 and 50) shows the rate of entrainment of mass decreasing in time, roughly from 0.15 to 0.06, as expected once the entrainment rate at the head is ruled by local reduced gravity: as current develops and ambient fluid is being entrained into the current, local density decreases and so does local reduced gravity, causing less fluid to be entrained. This should tend to an equilibrium state, not seen in this experiment due to geometric constraints. The observed cyclic behaviour of the current head shows an average periodicity of 3.4 s; gate removal induces small oscillations in the free surface, though with low energy and uncorrelated periodicity (average period of 0.8 s), thus independent from the breaking cycles. These breaking cycles however show that a limit exists in the entrainment capacity of the head, indicating an instability process eventually controlled by a dynamical quantity. After this limit is attained, the head breaks leaving behind a signature corresponding to *quasi*-steady ejection-type structures, visible in Fig. 2 at positions $(x\text{-}x_0)/x_0$ = 7.5 and 9.5 for instance, which eventually fade in time by diffusivity-type processes.

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