Experimental Investigation of Flow Structure of a Density Current Encountering a Basal Obstacle

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Due to the significance of density currents and with regards to the control of such important flows the flow structure of a density current encountering a basal obstacle in a rectangular channel is investigated experimentally by a 3D Acoustic Doppler Velocimeter. It was shown that the obstacle causes the distribution of turbulent kinetic energy of the flow to be changed significantly such that at its downstream the turbulent intensity profiles appears to have a non-uniform distribution over the height. Also it was shown that the turbulent kinetic energy has larger magnitude in downstream of the obstacle. In addition, in the presence of the obstacle, the variation of the local Froude number seems to be more significant over the channel length at its downstream which is compatible with the changes in turbulent kinetic energy. Moreover, it was quantitatively confirmed that in the absence of the obstacle, as the inlet Froud number increseas from subcritical to the supercritial flow, the turbulent intensities along the channel seem to increase.

Keywords: Density current, flow structure, turbulent intensity, Froud Number, Obstacle, ADV.

1 INTRODUCTION

Many geophysical flows are classified as gravity or density currents, as they occur due to a density difference with the surrounding environment [1]. Density currents can be considered observed manifestations of interactions between an ambient flow and a horizontal buoyant intrusion [2] and are produced where gravity acts upon a density difference between two fluids. In the case of suspension currents such as turbidity currents, density excess is provided by suspended solid particles.

Density currents are of considerable importance from many perspectives as they play a major role in the transport of sediment on land, in lakes, seas and into the deep oceans [3] and thus their control is of significance. They pose various potential hazards such as submarine cable breakage, destroying sea-floor equipments etc. [4]. They also pose danger to submarines and therefore should be properly predicted to provide information on the safe navigation path for them.

Specifically, in an environmental context, turbidity currents are responsible for much of the sedimentation in reservoirs [5], with consequent loss of water storage capacity [6]. Therefore, turbidity currents also provide an important mechanism for transfer of sediments. One application of the control of such flows can be the ultimate goal of controlling or management of sedimentation in dams. There are some methods to control the density currents, amongst them using the standing barriers have been regarded as a way to control them. The dynamics of deposition in quasi-steady or steady turbidity currents can be usually controlled by the topographic obstacles in the flow path [7]. It is noted that sea-floor topographies can also influence the pattern of sedimentation in ocean or sea floors [8].

With regards to the utilization of obstacles for density current control, some investigations have been performed in the literature. For example, Oehy and Schleiss [9] examined the placement of an obstacle before a reservoir to control the sedimentation in a reservoir. Their findings show that turbidity currents could be affected well by appropriately designed constructive measures. Kneller & Buckee [10] reviewed some studies on the structure and fluid mechanics of turbidity currents, saying that when sediment gravity flows face with the topography which is not completely flat, the topography influences deposition significantly.

Therefore, it is also important to reveal how such barriers affect the turbulent structure of the flow since the turbulent structure could influence the deposition behavior of turbidity currents (e.g. resuspend sediments) [11]. As this effect has not been explored very systematically, therefore, in this paper the effect of a triangular obstacle on the flow structure of a density current is experimentally investigated by using a 3D Acoustic-Doppler-Velocimeter (ADV) which is capable of measuring the instantaneous velocity at each point in space in three directions. The main focus will be the turbulent structure of the turbidity current and the effect of the inlet Froude number.

2 EXPERIMENTS

2.1 Experimental setup

All the experiments have been performed in a rectangular channel flume specially designed for the generation of density currents resulting from the release of turbid water on a sloping surface in a 12 m long, 0.2 m wide and 0.6 m high channel of fresh water with a glass side walls to provide visualization of the flow. The schematic view of the experimental set-up is shown in Fig. 1.

The channel is divided into two sections in the longitudinal direction using a separating Plexiglas sheet. The shorter upstream section accumulates dense fluid with a sluice gate in its rectangular bottom. The adjustable opening gate allows changing the inlet velocity of the particle-laden fluid which is prepared in the supply tank using a mixture of water and Kaolin particles (d50=18µm) with density of 2650 kg/m^3. The channel was previously filled with fresh water and its temperature was the same as the laboratory temperature. At the beginning of the tests, by removing the gate the particle-laden fluid is continuously fed into the accumulator through the gate and then it flows down the sloping bottom under the fresh water. The slope of the channel is kept constant at 1%. The sediment-laden density current gradually spreads under the fresh water.

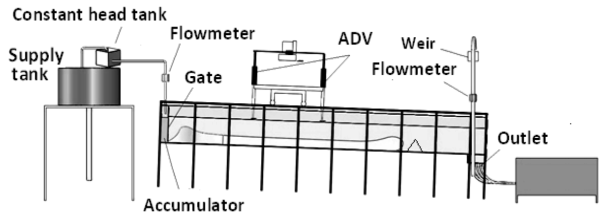

Figure 1: Schematic side view of the experimental setup

2.1 Experimental procedures

The velocities at each measurement point have been measured on the central longitudinal plane by a 3D ADV. This device is based on the principle of Doppler shift of a wave reflected from particles suspended in the fluid flow. Data can be available at an output rate of 25 Hz. The small sampling volume is located away from the sensor to undisturbed measurements resulting in accurate velocity measurements. Two down-looking probes of 10MHz-ADV have been utilized to measure the instantaneous velocities at various depths at several longitudinal sections along the channel.

Velocity profiles were measured at 5 sections along the channel located at x = 3.5m, 4.25m, 4.5m (obstacle position), 4.75m and 5.25m. x is the distance of from the inlet. Measurements started at the top part of the current and continued by dipping the probes until all the desired positions were covered. About 14 positions were considered to obtain the velocity profile at each station. The schematic view of the measuring sections is shown in Fig. 2.

First, the flow is measured for the case that there is no obstacle. In the next stages an isosceles triangular made of Plexiglas with the height of S_o=6 cm is positioned at x=4.5m as an obstacle. At each stage experiments were performed for three inlet conditions: (F_{in} =1.55, F_{in} =1, F_{in} =0.6).

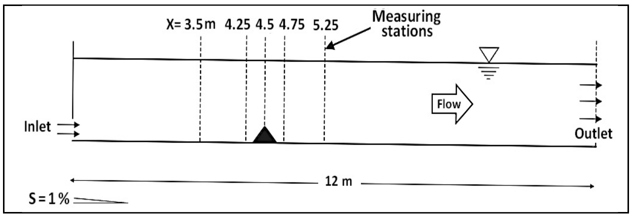

Figure 1: Schematic of measuring stations (numbers are in meter)

3 RESULTS AND DISCUSSION

3.1 General perspective of turbidity current facing with the obstacle

Turbidity current enters and flows through the channel and continues its path over implanted obstacle. While the head of the dense fluid faces the obstacle, it undergoes some changes in its shape. This phenomenon has been qualitatively shown in Figure 3-a, to 3-f which demonstrates some captured images of the sequences in a typical experiment. When the dense fluid passes over the obstacle (3-a to 3-e), it takes several minutes for the flow to reach the quasi-steady condition and the measurements start. Figure 3-f shows the quasi-steady condition for the mentioned experiment.

Also in Fig. 4 a typical longitudinal velocity distribution has been show quantitatively.

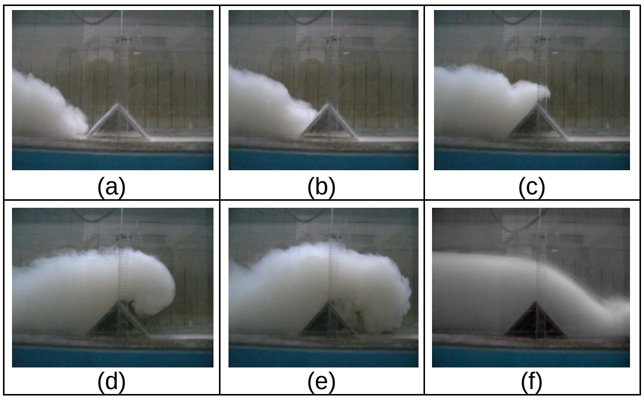

Figure 3: (a) to (e): Dense layer behavior passing over the obstacle, (f): The quasi-steady condition

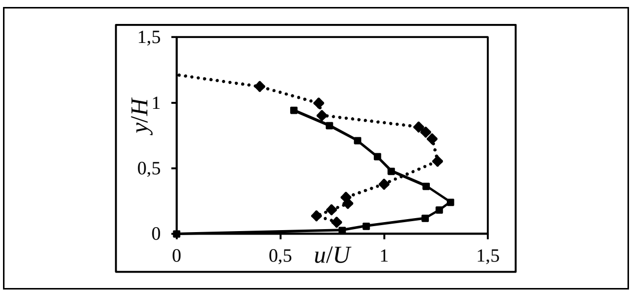

Figure 4: Longitudinal velocity profiles non-dimensionalized by layer-averaged velocity at a typical

station (x = 4.75 m from the inlet), when, F_{in}=1.55. Solid line (no-obstacle) and dashed line (obstacle) experiment.

3.2 Effect of obstacle on the turbulent structure

In order to investigate the effect of the obstacle on the turbulent structure of the flow, turbulent kinetic energy has been considered at measurement stations. Turbulent kinetic energy per unit mass denoted by *k* is defined as

$$k = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \quad (1)$$

where u', v', w' are the fluctuations of the velocity components in streamwise, normal and lateral directions, respectively. These fluctuations were obtained by ADV. Detailed investigation of turbulent structures in turbidity current flow requires precise evaluation of the friction velocity, U^*. This parameter is the most fundamental velocity scale. In the present research, turbulent kinetic energies have been normalized with this velocity scale. As a result, the friction velocity can be computed as:

$$U^* = \sqrt{\frac{\tau_w}{\rho_m}} \quad (2)$$

τ_w is the wall shear stress and ρ_m is the mixture density.

Distribution of the turbulent kinetic energy at various stations for no obstacle experiments (F_{in} =1.55, F_{in} =1, F_{in} =0.6) have been calculated and shown in Fig. 5. In all the figures, heights are non-dimensionalized with the layer-averaged height (*H*) which is defined later. There are also dashed lines, these lines indicate the current height (the current height is chosen as a height of the dense layer where the velocity becomes ¼ maximum velocity or briefly $z_{1/4}$ (Firoozabadi *et al.* [12]) which is non-dimensionalized with the layer averaged height. As can be observed from the figure, in the absence of an obstacle the kinetic energy does not vary significantly throughout the channel, for each inlet Froude number; however, an increase in the value of the inlet Froude number raises the corresponding kinetic turbulent energy.

It is noticeable that as shown in Fig. 6 in the absence of any obstacle, the turbulent intensities along the channel seem to increase when the inlet Fr. number increseas from subcritical to the supercritial value.

Implanting an obstacle causes the turbulence structure of the flow to change significantly. Fig. 7 shows the normal distribution of the turbulent kinetic energy for F_{in} =1.55, and for the case that a 6 cm-high obstacle has been installed. It is observed that at upstream of the obstacle the turbulent kinetic energy profiles are approximately the same as the no obstacle case with the same inlet condition. But, at downstream of the obstacle the turbulent kinetic energy seems to be about 2-3 times larger than its value at the upstream. This behavior could be as a result of the circulations that occur in the density current when it is going downward the obstacle. This change is very similar to the change of the local Froude number of the current which is shown for both experiments in figure 4. It is noted that the local Froude number at each station is calculated as follows:

$$F_{loc} = \frac{U}{\sqrt{g'H}} \quad (3)$$

where $U = \int u(y)^2 dy \Big/ \int u(y) dy$ and $H = \left(\int u dy\right)^2 \Big/ \int u^2 dy$ [13] and $g' = g\ \Delta\rho / \rho_a$. Also, $C = \int c(y) u(y) dy \Big/ \int u(y) dy$ and $\Delta\rho = \rho_m - \rho_a \approx C$ in which ρ_a is ambient fluid density. Here, $u(y)$ and $c(y)$ are velocity and concentration distribution in the streamwise direction at distance *y* above the channel's bed which are obtained by ADV.

This similarity is predictable as the (local) Froude number is (locally) the proportion of inertia force which in turn makes the current more unstable, to the buoyancy force which stabilizes it. In no obstacle flow, the changes in the local Froude number appear not to be so much but for the other experiments with the obstacle the variation of the local Froude number seems to be more significant over the height which is compatible with the changes in turbulent kinetic energy.

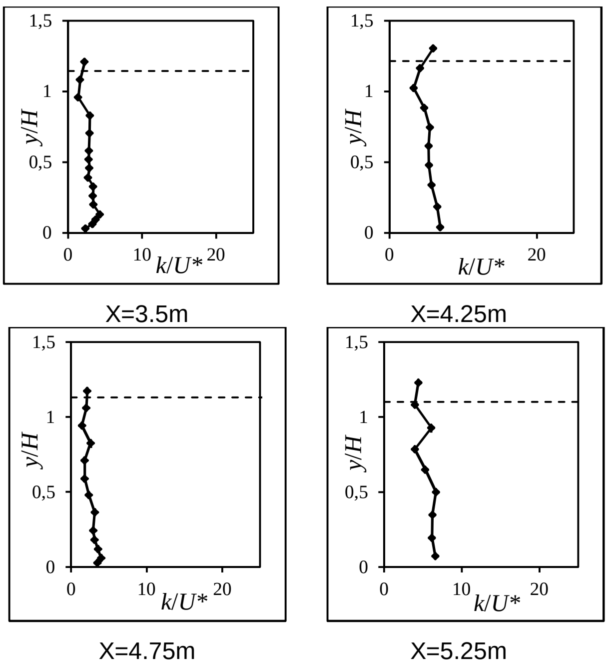

Figure 5: Typical profiles of the turbulent kinetic energy in normal direction for no-obstacle experiment for F_{in} =1.55, Dashed lines represent the currents height with respect to the layer averaged height.

In figure 8 the distribution of the local Fr Number in the absence and presence of the obstacle has been presented.

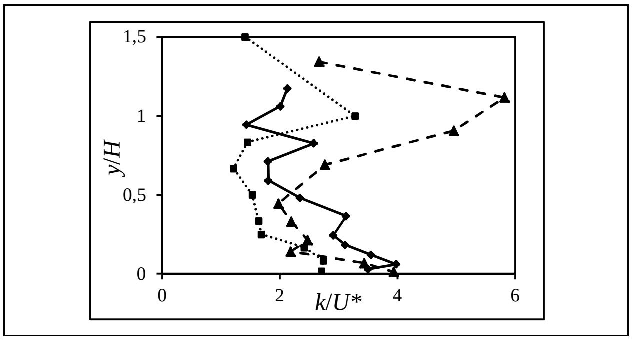

Figure 6: The comparison of the turbulent kinetic energy in normal direction for no-obstacle experiment: F_{in} =1.55 (solid line with diamonds), F_{in} =1 (dash line with triangles), F_{in} =0.6 (dot line with circles) at a typical section (x= 4.75 m from the inlet)

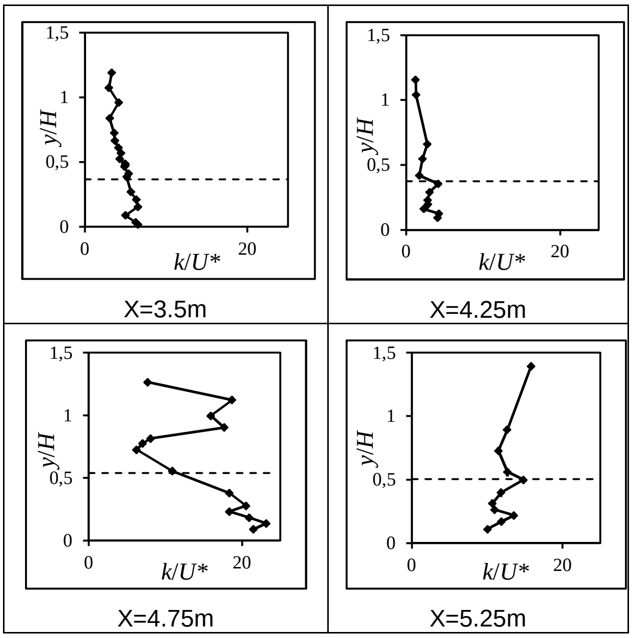

Figure 7: Typical profiles of the turbulent kinetic energy in normal direction for experiments with the obstacle: F_{in} =1.55, dashed lines shows the obstacle height with respect to the layer-averaged height.

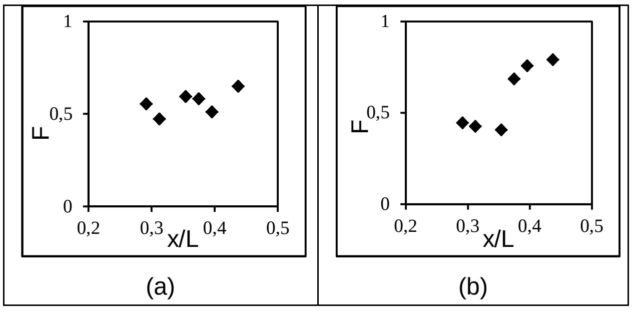

Figure 8: A typical distribution of the local Fr. numbers over the channel length for (a) no-obstacle experiments: F_{in} =1.55 and (b) with obstacle experiments: F_{in} =1.55.

6 SUMMARY

The flow structure of a density current encountaring a basal obstacle is investigated experimentally in a rectangular channel using a 3D ADV. Based on the obtined results of this investigation, the following conclusions can be made:

1. It was quantitatively confirmed that when there is no obstacle, the turbulent intensities along the channel seem to increase with the inlet Fr. number from sub-critical to the supercritial flow regime.
2. It was found that the obstacle causes the distribution of turbulent intensity profile to be changed. At the downstream of the obstacle the turbulent intensity profiles appears to have a non-uniform distribution over height. Also the turbulent kinetic energy seems to increase compared to its value at the upstream.
3. In the absence of any obstacle, the changes in the local Froude number of the flow appear not to be very considerable but in the presence of the obstacle the variation of the local Froude number seems to be more significant over the channel length at its downstream which is compatible with the changes in turbulent kinetic energy.

The result of this investigation could in turn be helpful in the prediction of the behavior of turbidity current facing with an obstacle.

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