Jurnal
Teknologi

Full Paper

EXPERIMENTS ON THE DYNAMICS OF DENSITY CURRENTS

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Article history
Received
10 March 2016
Received in revised form
22 May 2016
Accepted
25 May 2016

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Graphical abstract

Abstract

Density currents occur when fluid of one density propagates along a horizontal boundary into fluid of a different density. In dam reservoirs, density currents are the main transport mechanism for the incoming sediments and they play an important role in redistribution of existing sediments. This paper aims to investigate velocity structure in the body of density currents. To this end, laboratory experiments were performed on density currents having various initial conditions and bottom slopes. Then, vertical velocity profiles were recorded in the body of density currents. The velocity structure of the currents was investigated by fitting equations to the wall and jet regions of the measured profiles, and the constants of the equations were yielded with R^2 more than *0.80*. Temporal and spatial evolution of density currents were also analysed to study the dynamics of the frontal region of the currents. It was observed that the currents having more bottom slope travel at a further distance. It was also found that 400% increase in the initial concentration of the currents can increase their frontal velocity up to 97%.

Keywords: Turbidity current, velocity profiles, front velocity, bottom slope, concentration

Abstrak

Arus ketumpatan berlaku apabila cecair dengan satu ketumpatan mengalir di sepanjang sempadan mendatar ke dalam cecair yang berbeza ketumpatan. Dalam takungan empangan, arus ketumpatan adalah mekanisme pengangkutan utama bagi sedimen masuk dan ia memainkan peranan penting dalam pengagihan semula sedimen sedia ada. Kertas kerja ini bertujuan untuk mengkaji struktur halaju dalam badan arus ketumpatan. Untuk tujuan ini, ujikaji telah dijalankan dengan menggunakan pelbagai kepekatan dan cerun dasar. Kemudian, profil halaju menegak telah direkodkan di dalam badan arus ketumpatan. Struktur halaju telah disiasat dengan menggunakan persamaan yang sesuai untuk profil kawasan dinding dan jet yang diukur dan regressi, R^2 yang diperolehi di antara persamaan dan data pengukuran adalah lebih daripada 0.80. Evolusi ruang dan masa arus ketumpatan juga telah dianalisis untuk mengkaji dinamik arus di rantau hadapan. Keputusan diperolehi menunjukkan dengan menaikkan cerun dasar dan kepekatan awal akan meningkatkan halaju arus hadapan. Kesimpulannya, arus berketumpatan yang mempunyai kepekatan masuk yang tinggi akan mengalir pada jarak yang lebih jauh.

Kata kunci: Arus kekeruhan, profil halaju, halaju hadapan, cerun dasar, kepekatan

1.0 INTRODUCTION

Stratified flows and the related flow processes attract scientists of various disciplines. Density currents are generated when fluid of one density is released into fluid of a different density [1]. These currents can be created even by a small density difference of only a few percent [2]. The density difference can be resulted from temperature gradients, dissolved contents, suspended particles or a combination of them[3]. The currents are produced by gravity acting upon a density difference between lighter and denser fluids, thus such currents are also termed as gravity currents[4]. The currents are known as turbidity currents in case the main driving mechanism is obtained from suspended sediments[2].

In oceanic and river systems, the density difference between saline oceanic water and fresh river water can create river plumes and salt edges[5]. These flows are the main sediment transport mechanism in deep submarine environment, traveling long distances and transforming the topography of ocean floor. In dam reservoirs, turbidity currents are an important agent for sediment transport. Normally, these currents occur when there is a flood and follow the thalweg toward the deepest area of the reservoir close to the dam [6]. This is where the current deposits and covers the bottom outlet or affects the operation of water intake structures [7].

Sediment discharge of rivers flowing into reservoirs is typically very high during flood events. As the turbid flood flows to fresh water of the reservoir, the turbid inflow displaces the ambient water until it reaches a balance of forces and then it plunges under the water surface [8]. This region is named plunge point and is typically located downstream of area of delta deposition in reservoirs[9]. Thereafter, turbidity current is formed propagating over the reservoir bed.

The leading edge of density currents is called head (also known as front) which is deeper than the following flow (body) and has a raised nose at its foremost point. The schematic of a density current propagating over a sloping bed and under a layer of stationary ambient fluid having a density (ρ_a) less than that of the density current (ρ_d) illustrated in Figure 1. The highest point of the front is known as its height (H_f) travelling with the velocity of U_f. For the body, the height and velocity are shown with h and u, respectively.

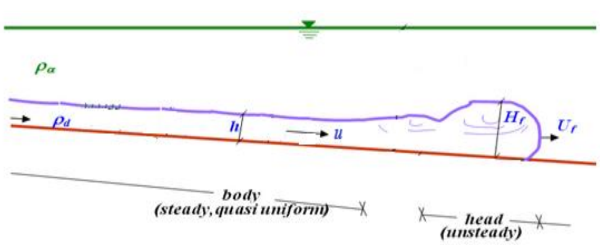

Figure 1 Sketch of a density current advancing over a slope

The in situ studies show that turbidity currents are the main transport mechanism for the incoming sediments and that they play an important role in redistribution of sediments within dam reservoirs through entrainment and deposition of sediments[10].

In case of steep bottom slopes in narrow reservoirs, turbidity currents are the main mechanism for transporting and depositing of sediments [11, 12]. Turbidity currents can be of high velocities, depending on the slope of thalweg [13] and features of the bed over which they travel. Therefore, even the existing sediment deposits can be suspended again and transported toward the dam [14]. Reservoir sedimentation can also block bottom outlets, reduce the capacity of reservoir and harms the dam power plants [13, 15]. Moreover, some environmental problems can be posed by the reservoir sedimentation for example its influences on water quality, aquatic life and nutrient supply at the downstream [16].

Tackling sedimentation problems and improving reservoir operation require understanding the dynamics of density currents in dam reservoirs. This paper aims to investigate the velocity structure in the body of density currents. It also analyses the dynamics of the frontal region of these currents under different initial conditions.

2.0 METHODOLOGY

To model density currents in the laboratory, a specific setting is required that could prepare dense fluids and maintain the steady state of density currents during the course of experiments. An appropriate experimental apparatus was prepared consisting of five main parts: water supply system, mixing tanks, head tank, flume and drainage system. The experimental set up is shown in Figure 2.

Figure 2 Experimental set up

During the experiments, fresh water was required to keep the depth of ambient fluid constant in the flume and replaced the ambient fluid entrained by the density current. Also, fresh water was needed for producing dense fluids in the mixing tanks.

Next to the flume, there were two mixing tanks with a maximum volume of 6 m^3 to prepare dense fluids through continuous circulation in a closed loop system that was separated from the flume. Salt was dissolved in tap water inside the tanks until the required salinity was obtained and the solution was homogeneously mixed. For visualization purposes, dye was also added to dense fluids during the circulation process. The prepared dense fluids had to be transferred to flume with a constant head in order to prevent fluctuations. For this reason, a head tank was used located 3 m above the ground on a steel structure.

The flume was 10 m long, 0.3 m wide and 0.7 m deep capable of having variable bed slopes. A sliding vertical gate was constructed, dividing the flume to two sections of unequal length. The gate was situated at 1.25 m distance from the upstream end of the channel. The upstream of the gate was filled with dense fluid while the downstream part was filled with fresh water. The long downstream section simulated a reservoir where a density current is propagating. An overflow weir was placed at the downstream end of the flume, keeping the depth of lighter ambient fluid constant during each experiment. At the downstream end of the flume, a drainage system was needed to direct the density current for withdrawal. To this end, a drainage system was made consisting of four 1 inch drainage pipes and a gutter.

The flow discharge could be adjusted by the means of a valve and using an electromagnetic flow meter prior entering the flume. The experiments started with the sudden removal of the gate. The gate was opened 7 cm in all experiments. Nine experiments were performed with a fixed discharge of 1 L/s, having different bottom slopes and initial concentrations as shown in Table 1. A Nortek Acoustic Doppler Velocimetre (ADV) with 10 MHZ acoustic frequency was used to record the velocity profiles in the body of density currents at three locations (i.e. X= 3 m, 4 and 5 m from the gate) along the centreline of the channel. In this study, samples with signal-to-noise (SNR) values less than 15 dB and correlation less than 70% were filtered. For each experiment, the evolution of the front was also recorded by videotaping.

Table 1 Experimental parameters

Experiment number	1	2	3	4	5	6	7	8	9
Bottom slope (S) %	0.25	0.25	0.25	1	1	1	1.75	1.75	1.75
Inlet concentration (C_{in}) g/L	5	15	25	5	15	25	5	15	25

3.0 RESULTS AND DISCUSSION

Non-dimensional numbers are used to determine density current regimes. The densimetric Froude Number (Fr_{in}) is defined as $Fr_{in}=\upsilon_{in}/(g'h_{in}\cos\theta)^{0.5}$ where υ_{in} is the inlet velocity, h_{in} is the inlet opening height, g' is reduced gravitational acceleration and θ is the bottom slope. The reduced gravitational acceleration (g') is $g'=g(\rho_d-\rho_a)/\rho_a$ where g is the gravitational acceleration. In our experiments $0.59<Fr_{in}<0.97$.

The inlet Reynolds number in these currents is defined as $Re_{in}=\upsilon_{in}\ h_{in}/\upsilon$ where υ is the kinematic viscosity of inlet mixture. This can be rewritten as $Re_{in}=Q_{in}/b\ \upsilon$ where the b is the flume width. Hence, in our experiments, the inlet Reynolds Number was equal to 3912.

3.1 The Body Of Density Currents

The velocity structure in the body of saline underflows is investigated herein. To this end, a total of 27 vertical velocity profiles were collected in laboratory experiments. The typical velocity profiles of density currents has an inner (wall) and outer (jet) region as seen in Figure 3 where u is the velocity of the current at the depth of z. These regions are separated by maximum velocity (u_m). The distance above the bed where the maximum velocity occurs is referred to as hm.

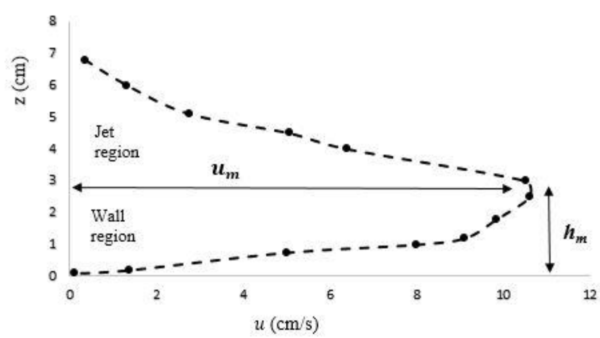

Figure 3 Velocity profile at X= 3 m for the experiment 9

The boundary between the density current body and the ambient fluid is normally unclear, thus Ellison and Turner [17] calculated layer-averaged velocity ($\bar{u}$) and height ($\bar{h}$) of density currents as

$$\bar{u}\bar{h} = \int_0^{h_d} u(z)\,dz \tag{1}$$

$$\bar{u}^2\bar{h} = \int_0^{h_d} u(z)^2\,dz \tag{2}$$

Where $u(z)$ is local velocity at the depth of z and h_d is the depth where the velocity is zero.

To further investigate the flow structure, in our experiments we found that

$$\frac{h_m}{\bar{h}} = 0.41, \qquad \frac{u_m}{\bar{u}} = 1.19 \tag{3}$$

In all the experiments, velocity profiles were similar, but scattered in a specific range. Two different algebraic expressions, which are valid in jet and wall regions, were used to evaluate the velocity distribution in our experiments.

The flow is controlled by the bottom friction in the wall region and Altinakar et al. [18] suggested that the velocity distribution follows an empirical power relation as

$$\frac{u\,(z)}{u_m} = \left(\frac{z}{h_m}\right)^{\frac{1}{n}} \tag{4}$$

Where n is an exponent.

In the jet region, turbulence is made in the free shear zone and water entrainment occurs at the outer edge. Altinakar et al. [18] proposed a near-Guassian relation for the velocity distribution in this region as

$$\frac{u(z)}{u_m} = exp\left[-\alpha\left(\frac{z-h_m}{\bar{h}-h_m}\right)^m\right] \tag{5}$$

Where α and m are empirical constants and $\bar{h}$ is the layer-averaged height defined by Eq 1& 2.

Eq 4 & 5 were fitted to the measured velocity profiles in the wall and jet regions to determine the constants n, α and m as defined in Table 2.

Table 2 The constants for Eq. 4 and 5

Contents	n	R^2	α	m	R^2
Value	2.188	0.829	1.781	1.816	0.889

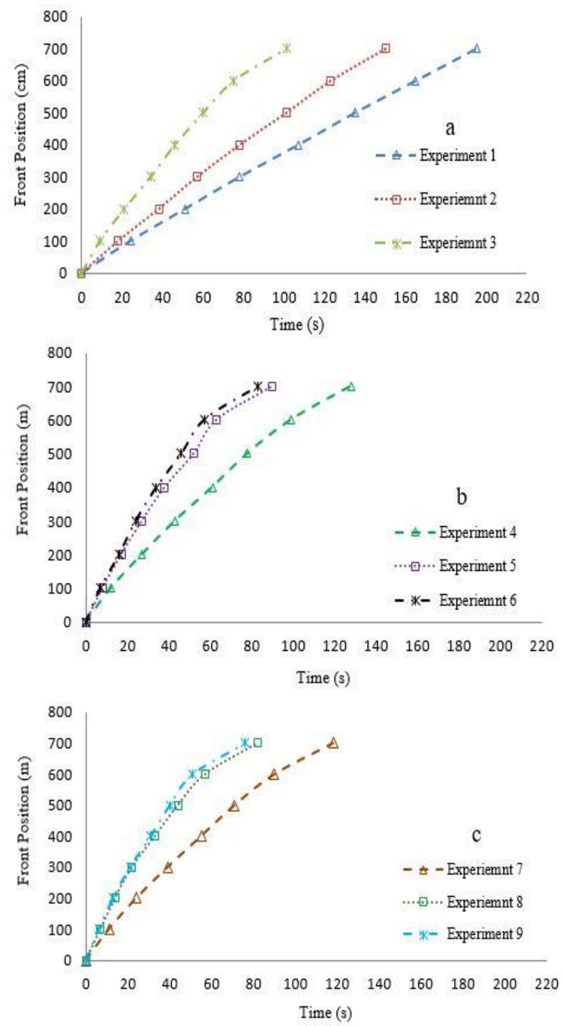

Figure 4 Front position versus time

3.2 The Front Of Density Currents

Figure 4 illustrates the temporal evolution of density current for different slopes, i.e. a: S= 0.25%, b: S=1% and c: S=1.75%. For experiments 1, 2 and 3; it took the density current 195s, 150s and 101s after the gate opening to reach a distance of 700 cm from the gate respectively. In case of experiments 7, 8 and 9; it took the currents 118s, 82s and 76s to travel 700 cm respectively.

For all the experiments, this is seen that in a given time, the gravity currents having more inlet concentrations travelled at a further distance. This means that the speed of the gravity currents increases as the inlet concentration increases, as was also observed in experiments done by [19].

Figure 5 shows the comparisons of the measured currents front profiles for selected experiments. The profiles are shown at three different times (t) after release, i.e. t=25 s, t= 50 s and t= 75 s. As seen in Figure 5a, the experiment carried out with C_{in}=5 gr/L covered a distance of 125 cm at 25 seconds after the gate opening. For C_{in}=25 gr/L, the covered distance increased 140% reaching to 300 cm from the gate. The driving force of density currents is the density difference between the current and ambient fluid [20]. Therefore, the density current advances slower as the inlet concentration decreases.

Figure 5b,c illustrate the front profiles 50 and 75 seconds after the gate opening. At t=50 s, for C_{in}=5 gr/L the density current travelled 212 cm. For C_{in}=25, the covered distance increased 118% reaching to 462 cm from the gate.

At t=75 s, the gravity current for C_{in}= 5 gr/L covered a distance of 350cm. Also, in case of C_{in}= 25 gr/L, the covered distances increased 107% reaching to 725 cm from the gate. This shows that the distance that was covered by the density currents increased when the currents were of higher concentration.

The head enlarges as travelling in the downstream direction, which can be attributed to growing amount of entrained fresh water into the head. The influx of this extra fresh water into the head results in a reduction in the head density excess, which is in agreement with findings of [21] examining flow of gravity currents over smooth and rough surfaces.

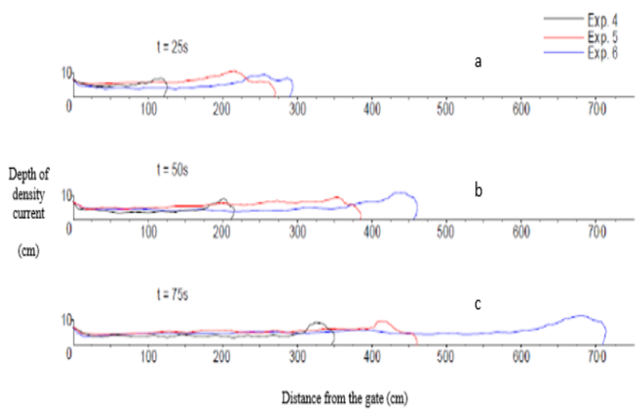

Figure 5 Comparisons of currents profiles for different times (t) ; a) t=25 s, b) t=50 s, c) t=75 s

Table 3 shows the mean frontal velocity of density currents propagating over different bed slopes and inlet concentrations. This shows that in this work two factors affected the frontal mean velocity of density current. Considering experiments with the same inlet conditions (e.g. experiments 1, 4 and 7), the frontal velocity increased on steeper slopes. For these experiments, the front velocity flowing over the bottom slope of S=1.75% was 68% more that of the S=0.25%.

Moreover, considering experiments with the same slope (e.g. experiments 1, 2 and 3), this is seen that the front velocity increased by increasing the inlet concentration. For these experiments, increasing the inlet concentration (from 5 to 25 gr/lit) resulted in a 97% increase in frontal velocity.

The experiment 9 had the highest mean frontal velocity (9.2 cm/s) and experiment 1 had the lowest velocity (3.5 cm/s).

Table 3 Frontal mean velocity

Experiment number	1	2	3	4	5	6	7	8	9
Velocity (cm/s)	3.5	4.6	6.9	5.4	7.7	8.4	5.9	8.5	9.2

4.0 CONCLUSION

Density currents can be created even by a small density differences in natural and manmade environments. This paper studies the velocity structure in the body of density currents. It also analyses the dynamics of the head of density currents under different initial conditions. Three different configurations of bed slopes and inlet concentrations were tested. Equations were developed for the distribution of velocity in the body of density currents. The spatial and temporal evolution of density currents fronts were also measured. Steeper bed slope also caused an increase in frontal mean velocity. For a given time, the observed general trend was that the density currents having more inlet concentration travelled at a further distance.

Acknowledgement

The funding for this work was provided by the Fundamental Research Grant Scheme (reference number: FRGS/1/2015/STWN01/UTM/02/2), under the Ministry of Education (Malaysia). The authors would also like to acknowledge the support of Universiti Teknologi Malaysia through the Research University Grant (reference number: PY/2014/02346).

References

[1] Marino, B., Thomas, L.and Linden, P. 2005. The Front Condition for Gravity Currents. *Journal of Fluid Mechanics.* 536: 49-78.

[2] Simpson, J.E. 1999. Gravity Currents: In the Environment and the Laboratory: *Cambridge University Press.*

[3] Nasrollahpour, R. and Ghomeshi, M. 2012. Effect of Roughness Geometry on Characteristics of Density Currents Head. *Indian Journal of Science and Technology.* 5(12): 3783-3787.

[4] Chowdhury, R.A. 2013. Effect of Roughness on Density Currents, in *Department of Mechanical Engineering*, The University Of Texas at San Antonio.

[5] Adduce, C., Lombardi, V., Sciortino, G.and Morganti, M. 2009. Roughness Effects on Gravity Currents Dynamics. *The Proceedings of the 33rd IAHR Congress, Canada*.

[6] Bühler, J., Oehy, C.and Schleiss, A. 2012. Jets Opposing Turbidity Currents and Open Channel Flows. *Journal of Hydraulic Engineering.* 139(1): 55-59.

[7] Oehy, C.D., De Cesare, G.and Schleiss, A.J. 2010. Effect of Inclined Jet Screen on Turbidity Current. *Journal of Hydraulic Research.* 48(1): 81-90.

[8] [8] Oehy, C.D. and Schleiss, A.J. 2007. Control of Turbidity Currents in Reservoirs by Solid and Permeable Obstacles. *Journal of Hydraulic Engineering*. 133(6): 637-648.

[9] Kostic, S. and Parker, G. 2003. Progradational Sand-Mud Deltas in Lakes and Reservoirs. Part 1. Theory and Numerical Modeling. *Journal of Hydraulic Research.* 41(2): 127-140.

[10] Nasrollahpour, R., Jamal, M.H., Ismail, Z., Ghomeshi, M.and Roushenas, P. 2015. The Influence of Roughness on the Propagation of Density Currents. *Malaysian Journal of Civil Engineering.* 27(Special Issue 2): 266-272.

[11] Jiahua, F. 1986. Turbid Density Currents in Reservoirs. *Water International*. 11(3): 107-116.

[12] Fan, J. and Morris, G.L. 1992. Reservoir Sedimentation. Ii: Reservoir Desiltation and Long-Term Storage Capacity. *Journal of Hydraulic Engineering*. 118(3): 370-384.

[13] Cesare, G.D., Schleiss, A.and Hermann, F. 2001. Impact of Turbidity Currents on Reservoir Sedimentation. *Journal of Hydraulic Engineering*. 127(1): 6-16.

[14] Sequeiros, O.E., Naruse, H., Endo, N., Garcia, M.H.and Parker, G. 2009. Experimental Study on Self-Accelerating

Turbidity Currents. *Journal of Geophysical Research: Oceans* (1978–2012). 114(C5).

[15] De Cesare, G., Oehy, C.and Schleiss, A. 2008. Experiments on Turbidity Currents Influenced by Solid and Permeable Obstacles and Water Jet Screens. *6th ISUD-International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering*. Czech Technical University in Prague-Institute of Hydrodynamics AS CR, vvi.

[16] Ghomeshi, M. 1995. Reservoir Sedimentation Modelling.

[17] Ellison, T. and Turner, J. 1959. Turbulent Entrainment in Stratified Flows. *Journal of Fluid Mechanics.* 6(03): 423-448.

[18] Altinakar, M., Graf, W.and Hopfinger, E. 1996. Flow Structure in Turbidity Currents. *Journal of Hydraulic Research.* 34(5): 713-718.

[19] Nasrollahpour, R., Ghomeshi, M.and Ahadiyan, J. 2012. Turbidity Currents Head Motion over Artificially Roughened Beds. *World Applied Sciences Journal* 19(9): 1278-1283.

[20] Fragoso, A., Patterson, M.and Wettlaufer, J. 2013. Mixing in Gravity Currents. *Journal of Fluid Mechanics.* 734: R2.

[21] Nasrollahpour, R., Jamal, M.H., Ghomesi, M., Ismail, Z.and Roushenas, P. 2015. Density Currents Dynamics over Rough Beds. *Applied Mechanics and Materials*. Trans Tech Publ.