Effects of Bottom Obstacle Structure on Density-Induced Flow

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Abstract. Density flows frequently occur in nature and some of them have caused serious consequences, such as sedimentation and saline water intrusion. In order to control density flows, the method like placing an obstacle has been proposed. In this paper, the influence of the height and position of obstacle and the salinity difference on the behaviors of lock-exchange density flow was studied experimentally by using high-speed camera and laser particle image velocimetry (PIV) technique. The experiments were conducted in a plexiglass flume whose height, width and depth were 1.8 m, 0.22 m and 0.3 m respectively. Besides, the bottom of the flume is smooth. The flume was separated by one board and the left side of the flume was filled by fresh water while the right side of the flume was filled by salt water. After the board was lifted, the salt water flow into the fresh water and formed a density flow. Obstacles were placed 0.05 m and 0.25 m away from the gate respectively. The velocity and flow field were measured by using the PIV technique. The results indicated that the existence of obstacles blocked the progress of density flow and the propagation distance of density current in the case without obstacle was much longer than the other one which contained obstacle. Additionally, it was observed that when the density flow was crossing over one obstacle, a re-acceleration process was happening at the head of the current, and the maximum velocity caused by this process was larger than the maximum velocity without obstacles. Besides, by comparing the obstacle and non-obstacle situations, the body velocity of density flow was greatly reduced at the front of obstacle. However, the effect of different obstacle positions on the maximum velocity of the head of density flow is not significant.

Keywords. Density Flow, Obstacle, Piv, Flow Field, Horizontal Velocity.

1. Introduction
Density flow refers to the relative motion of two kinds of fluids with similar density, which can be mixed with each other, and this motion is caused by the density difference [1]. Besides, during the motion, the fluids in each layer can basically maintain their original characteristics, and a global mixing phenomenon will not be occurred by the turbulence action at the interface. Density flow is a normal phenomenon in nature [2]. For example, muddy water enters the reservoir, rivers pour into the ocean, the convection of warm and cold air and the movement of clouds in the atmosphere. Based on the causing reasons of the density differences, the density flow can be classified as sediment density flow, temperature density flow and saline density flow. The sediment density normally happens at the top of the reservoir. Besides, sediment density will lead to lots of floating objects gathering around the dive site and sometimes even crossing the banks [3]. As a result, the passage of ships may be blocked. The temperature density flow has been commonly found in the cooling water inlet of thermal power plant. To explain, the hot water may be pumped back into the cooling system

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again, which could decrease the cooling efficacy of the generator, due to the hot water diffuse above the cold water surface. The saline density flow is usually observed at the estuaries, which spreads fan-shaped to the upstream. As a consequence, the urban water supply, farmland irrigation and river bed evolution in estuary area are affected.

Flume experiment is one of the main research methods in the density flow domain due to the difficulty to observe the density current in practice. Therefore, lots of scholars have carried out experimental research on the influence of obstacles on the motion characteristics of density flow. Liang Z et al. [4] carried out the flume experiments with lock-exchange density flow moving along a slope with high-speed camera to capture the movement of the density flow. The results indicated that negative vortices appear at the top as the density flow flowed over the obstacle. Yindian L et al. [5] used the open-gate flume to carry out the experiments and they used a stick which was smaller than water depth to simulate the rigid vegetation as an obstacle. The results showed that the submerged vegetation can block the movement of the density current, convert the kinetic energy of the density flow into potential energy, and reduce the velocity and vorticity of the head of the density flow. Yafei L et al. [6] used high-speed camera and laser particle image velocimetry (PIV) to study the motion characteristics of lock-exchange density flow when encountering obstacles of different shapes at a constant speed on flat slope. The result indicated that when the thickness of density flow was equal to the height of obstacle, the maximum height of density flow might be doubled. Seyed et al. [7] conducted the experiments by changing the position of obstacle and the roughness of riverbed, their results suggested that the transport capacity of density flow was reduced by 50% in the presence of obstacles and was reduced by 90% if the upstream roughness was increased. Khavasi E et al. [8] employed a three-dimensional Doppler velocimeter to measure the density flow near the obstacle. The result presented that the presence of the obstacles significantly changed the turbulent kinetic energy and makes the downstream turbulence intensity present non-uniform distribution. Ermanyuk et al. [9] studied the hydrodynamic load of the interaction between the density flow and the underwater cylinder through experiments. It was found when the cylinder was at the bottom, the hydrodynamic load was the largest, and decreased rapidly with the increase of the distance between the obstacle and bottom.

In summary, the current research will mainly focus on the head shape and average head velocity of the density flow, and there are fewer systematic studies on the effects of obstacle structure and location on the density flow. In this paper, PIV technology was used to conduct a series of flume experiments to study the flow field characteristics of the lock-exchange density flow when it encountered obstacles at different positions. The instantaneous contour, instantaneous velocity, flow field and cloud pictures of density flow were obtained by PIV system and CCD high-speed camera. The results of this paper can provide theoretical support for practical engineering.

2. Experimental Set-Up

Experiments were carried out in a rectangular organic glass flume. The flume was 1.8m-long, 0.22m-wide, and 0.3m-deep, with a smooth bottom. The left side of the flume was saline water while the other side was fresh water. An aluminium baffle plate was set in the middle to separate the left and right sides. In order to eliminate the fluctuating pressure caused by lifting the baffle plate at the beginning of experiments, wave-absorbing sponges were arranged on both sides. With the lifting of aluminium diaphragm, salt water intruded into fresh water and formed a density flow. The height of the obstacle is 5cm, the width is 3cm, and the length is 22cm, which is the same as the width of the flume.

In these experiments, the PIV equipment was produced by the American TSI company, mainly including image acquisition cards (Xcelera-CL PX4), CCD cameras (POWERVIEW Plus 4MP), synchronizers (610036 Laser Pulse Synchronizer), lasers (YAG Lasers). The tracer particles used were PIV system-specific particles with a diameter of 55μm. Figure 1 shows a schematic sketch of the experimental set-up. The observation area is 50cm × 15cm on the right side of the gate.
The fundamental cause of the density flow is the density difference, which is the fluids on the two sides of the vertical interface have different densities [10]. The reduction of gravity is an important characteristic of density flow [11]. The salt water with higher density moves under the fresh water with lower density, and the salt water surrounded by the upper fresh water will suffer less gravity due to the buoyancy of the fresh water [12]. The relationship between the effective acceleration $g'$ of gravity and the acceleration of gravity $g$ is as follows [13]:

$$g' = \frac{\rho - \rho'}{\rho'} g$$

(1)

Where $g$ is the acceleration of gravity, $\rho$ is the density of salt water, $\rho'$ is the density of fresh water. $\eta = (\rho - \rho')\rho$ is also called gravity correction coefficient [14].

![Experimental apparatus](image)

Figure 1. Schematic views of experimental apparatus.

The Reynolds number $Re'$ and Froude number $Fr'$ are defined as [15,16]:

$$Re' = \frac{\overline{U} h_0}{v}$$

(2)

$$Fr' = \frac{\overline{U}}{\sqrt{g' h_0}} = \frac{\overline{U}}{\sqrt{\eta g h_0}}$$

(3)

Where $\overline{U}$ is the average speed of density flow, $h_0$ is the water depth, $v$ is the kinematic viscosity.

Table 1 shows the experimental conditions and parameters. In Table 1, $h_{ob}$ is the height of obstacle, position is the distance from obstacle to gate.

| Run | $\rho$(kg m$^{-3}$) | $g'$(ms$^{-2}$) | $h_0$(cm) | $h_{ob}$(cm) | Position(cm) | $Re'$       | $Fr'$       |
|-----|--------------------|----------------|------------|--------------|--------------|-------------|-------------|
| 1   | 1023.18            | 0.2272         | 15         | 0            | -            | 10838.15    | 2.12        |
| 2   | 1023.18            | 0.2272         | 15         | 5            | 5            | 8971.292    | 1.75        |
| 3   | 1023.18            | 0.2272         | 15         | 5            | 25           | 8047.210    | 1.57        |

3. Results and Discussion

3.1 Flow Field

During the movement of the density flow, the internal structure is complicated. By studying the velocity distribution inside the flow field, the movement law of the density flow can be
understood intuitively. In the analysis of density flow velocity field, the method of combining flow field arrows and velocity cloud picture is usually used. In this way, the movement of the fluid can be characterized by the flow arrows, the velocity of the flow field can be reflected by the cloud picture, which is also one of the advantages of PIV velocity measurement [17].

Figure 2 shows the propagation process of density flow with an obstacle, which is obtained by superimposing the flow field vector diagram and the coloring diagram. When the density flow reached the obstacle, the density flow was obstructed by obstacle. In addition, part of the density flow was reflected back to the flow direction, and the other part moved vertically along the obstacle. Finally, the density flow continued to move to the right after passing the top of obstacle. It could also be seen at 8.4s, when the density current passed over the obstacle, two opposite vortices were formed on the upper and lower sides of the head.

![Figure 2. Propagation of density flow.](image)

3.2 Horizontal Velocity
The gravity flow is mainly horizontal flow, and the vertical component of velocity is very small. Hence, the horizontal velocity can approximately represent the speed of density flow along the flume.

Figure 3 shows the cloud picture of horizontal velocity field of obstacle at 5 cm at 2.0 s, 3.2 s, 4.4 s, 5.6 s, 6.8 s and 8.0 s after the gate was opened.

When the obstacle was placed at 5cm, the obstacle was relatively close to the gate, so the density flow was blocked by the obstacle as soon as it was formed. The motion process could be divided into three stages: the deceleration stage before the obstacle (a, b), the oblique
acceleration stage after the obstacle (c, d) and the horizontal acceleration stage after reaching the bottom of the flume (e, f).

In the deceleration stage, after the density current encountered the obstacle, it moved vertically upward along the obstacle. When the density flow reached the top of the obstacle, the upper part of it was reflected back to the flow direction, the lower part continued to move to the right through the top of the obstacle. Then, under the combined effect of gravity and initial velocity, it continued to move obliquely downward and entered the oblique acceleration stage, forming new vortex centers with velocity close to 0 m/s between saline and fresh water. There were two vortex areas in opposite direction at the head of the density flow, the upper right part was counterclockwise and the bottom left was clockwise. As the density flow reached the bottom of the flume, it entered the horizontal acceleration stage. At this stage, the head of the density flow continued to entrain fresh water in the counterclockwise direction to the right, and the thickness of the head gradually increased, showing a state of high head and low body. However, the continuous mixing of the head of density flow with fresh water caused the flow velocity to decrease, so the extreme value of the speed was not in the head area but in the middle and back of the head. In the horizontal acceleration stage, the interface between salt water and fresh water was very unstable, resulting in a thicker area with a velocity of 0 m/s between the two layers. This may be due to the intense exchange of water between the upper and lower layers under the joint action of gravity, density difference and inertia when the density flow moved to the bottom of the flume through oblique acceleration.

Figure 3. The cloud picture of horizontal velocity field of obstacle at 5 cm.

In the process of density current movement, due to the blocking effect of obstacle, backwater occurred in the 0-10 cm section. In the area with a height slightly smaller than the obstacle, the density difference and the flow velocity decreased gradually. Then the density difference in the triangle area on the right side of the obstacle gradually changed to zero and the velocity also gradually changed to 0 m/s.

In the 0-10 cm section, the fresh water flow in the upper part of the flume was affected by the backwater, and its thickness was small. As the density flow passed over the obstacle, the height of it decreased, and the thickness of fresh water flow in the upper part increased gradually. Besides, the whole velocity of fresh water in the upper part was smaller than that of density current in the lower part.

Figure 4 shows the cloud picture of horizontal velocity field of obstacle at 25 cm at 2.0 s, 3.2 s, 4.4 s, 5.6 s, 6.8 s and 8.0 s after the gate was opened.
As shown in figure 4, when the obstacle was placed at 25 cm, the density flow was relatively stable before reaching the obstacle, the motion process could be divided into three stages: the stable stage before the obstacle (a, b), the deceleration stage over the obstacle (c, d) and the oblique acceleration stage after crossing the obstacle (e, f).

In the stable stage, the front of density flow head was an acute angle with the bottom of flume, and there was a stable separation zone between salt water and fresh water, but the interface was irregular curve. The main influencing factors were the vortex and internal wave effects caused by the mixing of salt water and fresh water. Stable fluid density stratification and necessary disturbance sources were two necessary conditions for the formation of internal waves. When the density flow was stable, the stratification of salt and fresh water in the upper and lower layers of the flume tended to be stable, and vortices of various sizes were distributed at the interface of fresh and salt water. The motion of these vortices disturbed the stratified water, thus forming internal waves. Besides, the size of turbulent vortices was constantly changing during the generation, development and elimination. Therefore, the interface of stratified salt water is an irregular curve.

In the deceleration stage, the main motion characteristics of the density flow were roughly the same as that when the obstacle was placed at 5 cm. Part of the density current was reflected back to the current direction, and the other part continued to move beyond the obstacle. In the 20-30 cm section, due to the backwater produced by the obstacle, the density difference in the left area of the obstacle gradually decreased, and the flow velocity also gradually decreased. In addition, the interface between salt water and fresh water was clear.

In the oblique acceleration stage, the velocity of density flow decreased gradually in the 0-30cm section, and a right-angled triangle region with a velocity of about 0 m/s was formed on the left side of the obstacle. Similarly, in the 30-40cm segment, the density difference gradually approached 0, forming an isosceles triangle area between isosceles with a velocity close to 0 m/s. After the density flow passed over the obstacle and touched the bottom of the flume, the velocity continued to increase, and the maximum velocity of density flow in the whole process appeared at this stage.

In the stable stage, the velocity of freshwater flow in the upper part of the flume was smaller than that of the lower density flow. Besides, the volume of water in the flume was conserved, so the thickness of the density flow in the stable stage before encountered obstacle was less than 0.5 times of the water depth. In the deceleration stage, the freshwater flow in the upper layer was affected by the backwater from the lower density flow, the thickness of

Figure 4. The cloud picture of horizontal velocity field of obstacle at 25 cm.
freshwater flow gradually decreased in the 10-30 cm section, but the flow velocity changed little and was relatively continuous. During the acceleration stage, the velocity of the upper fresh water flow decreased in the 10-20 cm section, which may be affected by the backwater effect caused by obstacles. The density flow mainly moved obliquely from the bottom of the flume to the top of obstacle, and the vortices at the interface between the salt water and the fresh water were broken and disappeared.

Figure 5 shows the cloud picture of horizontal velocity field of obstacle at different positions (non-obstacle, 5cm and 25cm from up to down) at 5.6s and 8.0s after the gate was opened.

As shown in figure 5, the blocking effect of obstacle on the progress of density flow was obvious. In cases of obstacle, the maximum velocity of the density flow at 8.0 s was approximately the same in both cases, which means, changing the position of obstacle would not affect the maximum velocity, but the closer the barrier was placed to the gate, the earlier the maximum velocity of density flow appeared. Moreover, there was a re-acceleration process when the density flow crossed the obstacle, and due to this process, the maximum velocity of the density flow was larger than that of the case without obstacle.

![Figure 5. The cloud picture of horizontal velocity field at different obstacle positions.](image_url)

4. Conclusion
(1) Before density flow reaches the obstacle, it is mainly horizontal, and the velocity distribution is not uniform. Due to the violent mixing of the density flow head and fresh water, the maximum velocity position is not at the head part of it, but in the middle and back of the head. The region with a velocity of 0 at the interface of salt and fresh water is the centre of vortices. With the stabilization of the density flow, the vortex centers are connected to form a stable stratified motion. However, when the density flow encounters obstacle, the stable stratification is broken.

(2) The existence of obstacle blocks the progress of density flow. Besides, the higher the obstacle is, the more obvious the effect of reducing density flow is. When the density flow passes over the obstacle, the density difference in front of the obstacle will be decreased more due to the existence of the obstacle, so the flow velocity in this area will be gradually reduced. However, after passing over the obstacle, the flow velocity at the head of the density current will have an acceleration process. The current will move obliquely downward at an angle of approximately 30° to 45° from the vertical, and form a new density current.

(3) The effect of different obstacle positions on the maximum velocity of the head of density flow is not significant. Compared to obstacles placed upstream, the average velocity of the density flow with the obstacles placed downstream is larger in the early stage, but the
average velocity will gradually decrease along with the density current passes over the obstacles. Besides, the closer the barrier is placed to the gate, the earlier the maximum velocity of density flow appears. However, the maximum velocity of density current after passing through obstacles is larger than that without obstacles.

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