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PROPAGATION CHARACTERISTICS OF DENSITY CURRENTS AND IMPLICATIONS TO POLLUTANT TRANSPORT IN A STRATIFIED RESERVOIR

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Abstract: Characteristics of density currents were first experimentally investigated in a pilot stratified reservoir with a length of 2.0m and a depth of 0.54m, in which the thermal stratification was achieved with a heating method. When the stratification stability indexes were of $0.0112 \sim 0.0197$ m$^{-1}$ and the buoyancy frequencies were of $0.3314 \sim 0.4393$ s$^{-1}$, the turbid inflow was observed to separate from the bed slope and to propagate horizontally into its equilibrium layer, namely interflow. The separation depth of density currents and the thickness of the interflow were both smaller in the strong stratification cases than those in the weak cases, which had an important impact on the pollutant transport in the reservoir.

Propagation characteristics of density currents and its implications to pollutant transport were systemically explored by numerically simulating behaviors of density currents under different conditions of stratification stability index, inflow velocity and sediment content of inflow. After careful calibration of Euler-Euler model, the simulated separation depth of density currents and the thickness of the interflow agreed well with the experimental ones, which showed the propagation of inflow was closely related to the stratification level. Impacts of inflow velocity and sediment content of inflow on the propagation of density currents were different under the simulated conditions. When the volume fraction of sediment in the inflow was increased from 0.025% to 0.20%, the separation depth of density currents was decreased from 21.0cm to 18.5cm, the thickness of the interflow was slightly increased from 6.2cm to 7.8cm, but the heights of the internal hydraulic jump were almost the same. The inflow velocity mainly influenced the time of developing the interflow, the developing time decreased as the inflow velocity increased, which implied the water quality would deteriorate quickly after a heavy rainfall. Under larger inflow velocity conditions, mixing between the inflow and background water was stronger due to the higher energy carried by the inflow, and this caused the larger depth of interflow and the bigger height of internal hydraulic jump, which indicated the pollutants carried by turbid inflow would be transported more widely.

Keywords: Stratified reservoir; density current; propagation; pollutant transport

INTRODUCTION

Water quality in a reservoir is undoubtedly important. Hydrodynamic processes play an important role in the formation of water quality and the biological productivity of reservoirs. Generally, the density difference between the inflow and the impounded water in a reservoir
determines the hydrodynamics after the inflow water enters the reservoir[1]. The density differences between the inflow and the background water in a reservoir may be due to differences in water temperature, concentrations of dissolved or suspended substances, or a combination of these. Inflows occur as overflows, interflows or underflows, depending on this density difference [2]. During the stratified period, the inflow temperature is always less than the temperature of the surface water, but higher than the temperature of the bottom water. The inflow forms an underflow followed by an intrusional interflow and its fate is linked to vertical mixing in the water column [3-4].

With global warming, the frequency and intensity of extreme rainfall events were predicted to change more dramatically in the near future while the amount of total precipitation will change slightly [5]. Large volume of turbid inflow will enter the source water reservoir after a heavy rainfall [6], and evolve in various types of density currents depending on the density difference between the inflow and background water. Density currents play an important role in the thermal structure and pollutant transport in the reservoir. Understanding the behaviors of density current is fundamental to study the changes of source water quality during the flooding season [7].

Plenty of work has been done on the density currents in unstratified lakes or reservoirs. Fan developed the empirical relationship between the mixing coefficients and Ri of density currents and bed slope[8]. When the composition of sediment is fine and sediment concentration less than 400kg/m³, Li et al discussed the criterion of plunge point of density current[9]. And many scholars have studied the form of reservoir sedimentation or plunge district at Xiaolangdi project in China[10]. However, the thermal stratification affects the development of density currents and the migration of contaminants or sediment at certain extent [8], and little has been reported on density currents in stratified waters. Density currents play an important role in the thermal structure and pollutant transport in the reservoir [11-13]. Understanding the behaviors of density current is fundamental to study the changes of source water quality during the flooding season.

1. NUMERICAL SIMULATION METHODS AND CONDITIONS
A two-dimensional mesh as shown in Fig. 1 was generated for a pilot stratified reservoir with a length of 2.0m and a depth of 0.54m using GAMBIT. The 2D mesh was refined locally and consisted of 8411 cells and 5654 nodes.

![Two-dimensional mesh for the pilot reservoir](image)

The density currents were simulated with the Euler-Euler multiphase model and a Renormalization-group (RNG) $\kappa-\epsilon$ model. The sediment concentration was expressed as volume fraction of sediment in the water. Velocity-inlet was used to describe the water-inlet of the simulated region. Outflow was used to describe the water-outlet of the simulation region.
Based on the measured data of water temperature of the pilot reservoir, the vertical distributions of water temperature as shown in Fig. 2 were imposed with the patch function of Fluent. The water density and viscosity were functions of water temperature, and their relationships were imposed with the user defined function (UDF) before simulation.

Fig. 2 Vertical distributions of water temperature under different stratification levels

For the verification cases, the detailed simulation conditions were listed in Table 1. To further investigate the effects of sediment concentration and velocity of inflow on propagation characteristics of density currents and pollutant transport, 4 levels of sediment concentration and velocity of inflow were used.

| Table 1: Different simulation conditions for the verification cases |
|------------------------|-------------|-------------|-------------|-------------|-------------|-------------|
|                         | M1 Experiment | M2 Experiment | M3 Experiment | M3 Experiment |
| Velocity (m/s)          | 0.0052749     | 0.0052749     | 0.0052749     | 0.0052749     |
| Density of mixed water (kg/m³) | 1001.707      | 1001.702      | 1000.089      | 1001.088      |
| The density of the upper layer (kg/m³) | 994.678       | 995.204       | 995.65        | 995.645       |
| The density of the water bottom (kg/m³) | 996.746      | 996.702       | 996.746       | 996.702       |
| Temperature of imported mixed water (°C) | 26.3        | 26.3        | 26.5        | 26.5        |

2. MODEL VERIFICATION

It can be obtained from experimental data of Wuhan University [11], when the water wasn’t thermally stratified, the density currents were generated as under-current (Case M4). Under stratified conditions (Cases M1-M3), the density currents were mainly characterized as interflow, which were similar to those as shown in Fig. 3.

The hydraulic separation phenomenon in stratified flow is called the internal hydraulic jump. The separation point of hydraulic jump was defined as the position where the direction of the velocity at the midpoint of the header section of inflow changes, and the thickness of that section is defined as the interflow thickness. According to the Qian and Zhang et al.[14-15], this phenomenon was related to the density ratio of two water layers. Froude Number of density and friction resistance. From Fig. 3, it can be concluded that the density currents would cause hydraulic separation between underflow and interflow under the stratified condition. When the water temperature gradient was smaller, the phenomenon of hydraulic separation got more obvious. Under strong stratification conditions, hydraulic separation occurred within the thermocline; on the contrary, under weak stratification conditions, hydraulic separation phenomenon occurred outside thermocline and even could cause the muddy water to transport...
and diffuse to the water surface areas. In the actual reservoir, this kind of phenomenon could cause the pollutants transmitted form the lower area to the upper area, which causes the deterioration of surface water quality.

Compared with the experimental data, the simulated results as shown in Table 2 agreed well with the experimental data, the correlation coefficients were all higher than 0.97. This indicated that the developed Euler-Euler multiphase model can be used to satisfactorily simulate the density currents under different conditions.

**Table 2 Verification of simulated results**

<table>
<thead>
<tr>
<th>Working Condition</th>
<th>M1 M1 Experiment</th>
<th>M2 M2 Experiment</th>
<th>M3 M3 Experiment</th>
<th>Correlation coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of separation point (cm)</td>
<td>17.0 17.2</td>
<td>18.2 18</td>
<td>19.8 18.8</td>
<td>99.67%</td>
</tr>
<tr>
<td>Thickness of interflow (cm)</td>
<td>4.5 4.5</td>
<td>5.5 6.0</td>
<td>7.0 6.5</td>
<td>97.69%</td>
</tr>
<tr>
<td>Thickness of thermocline (cm)</td>
<td>8 8</td>
<td>8 7</td>
<td>4 3</td>
<td>99.02%</td>
</tr>
</tbody>
</table>
3. PROPAGATION CHARACTERISTICS OF DENSITY CURRENTS

3.1 Effects of sediment concentration of inflow

From the results of model verification, it can be found that formation of interflow under the condition of weak stratification occurred outside the thermocline significantly. Therefore, the weakly stratified condition of Case M3 was selected for the stratification level in the following study. The sediment volume fractions of inflow were set as 0.05%, 0.025%, 0.1% and 0.2% respectively, and the simulated results were shown in Fig. 4. The depth of separation point seemed to reduce with the sediment concentration of inflow, and detailed results can be seen in result in Table.3.

![Fig. 4 Vector profiles of density flow under different sediment volume fraction conditions](image)

As the volume fraction of sediment of inflow increased, the water flow entering the reservoir would be accelerated due to the larger kinetic energy carrying from inflow. When the flow entered into the thermocline, the interflow would get much thicker. According to the principle of conservation of energy, the kinetic energy would increase, while the potential energy would decrease when the turbid inflow entered the large water body. Hence, the depth of separation point would decrease. For the height of internal hydraulic jump, its value was not sensitive to the volume fraction of sediment of inflow. According to Equation 1, the height of internal hydraulic jump is positively related to the Froude Number \((F_d)\) of density. When the volume fraction of sediment of inflow increased from 0.025% to 0.2%, the Froude Number \((F_d)\) of density didn’t change much, so the heights of internal hydraulic jump were almost the same

\[
\Delta h = \frac{1}{2} \left( \sqrt{1 + 8 F_d^2} - 1 \right)
\]

Table.3 Comparisons simulated results of different volume fraction conditions

<table>
<thead>
<tr>
<th></th>
<th>0.025%</th>
<th>0.05%</th>
<th>0.1%</th>
<th>0.2%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of separation point(cm)</td>
<td>21</td>
<td>19.8</td>
<td>19.0</td>
<td>18.5</td>
</tr>
<tr>
<td>Thickness of interflow(cm)</td>
<td>6.2</td>
<td>7.0</td>
<td>7.1</td>
<td>7.8</td>
</tr>
<tr>
<td>Times(s)</td>
<td>18400</td>
<td>10000</td>
<td>8100</td>
<td>4800</td>
</tr>
<tr>
<td>Height of internal hydraulic jump (cm)</td>
<td>3-4</td>
<td>4-5</td>
<td>3-4</td>
<td>3-4</td>
</tr>
</tbody>
</table>
3.2 Effects of inflow velocity
When the discharge of storm runoff is large, the mixing between the turbid inflow and background reservoir water will be stronger and faster, and this will result in the quick deterioration of reservoir water quality. The weakly stratified condition of Case M3 was also selected for the stratification level in this study. The inflow velocities of inflow were set as 0.01, 0.005, 0.0025 and 0.00125 m/s respectively, and the simulated results were shown in Fig. 5. Analysis is also focused on the interflow under the different velocity conditions. Under the condition of thermal stratification, as the inflow velocity increased, the kinetic energy carrying from the inflow would increase, and this would cause the depth of interflow to move to the bottom of thermocline making the separation point deeper and forming the phenomenon of water jump.

![Fig. 5 Vector profiles of density flow under different inflow velocity conditions](image)

It can be seen from the above results that the inflow velocity not only influenced the formation of interflow, but the position of the separation point (See Table 4). Due to the large water body momentum carrying from inflow, the thickness of the header section got thicker while the inflow velocity increased. When the header section expanded to the thermocline, the energy loss became larger which caused the height of hydraulic separation lower. When the inflow velocity was small, the diffusion area of pollutant would expand to a greater scope.

<table>
<thead>
<tr>
<th>Depth of separation point(cm)</th>
<th>0.01m/s</th>
<th>0.005m/s</th>
<th>0.0025m/s</th>
<th>0.00125m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of interflow(cm)</td>
<td>19.2</td>
<td>19.8</td>
<td>20</td>
<td>22</td>
</tr>
<tr>
<td>Times(s)</td>
<td>8.0</td>
<td>7.0</td>
<td>6.5</td>
<td>6</td>
</tr>
<tr>
<td>Height of internal hydraulic jump (cm)</td>
<td>7000s</td>
<td>10000s</td>
<td>23000s</td>
<td>40500s</td>
</tr>
<tr>
<td>Range of diffusion(m)</td>
<td>3–4</td>
<td>5–6</td>
<td>6–7</td>
<td>7–8</td>
</tr>
</tbody>
</table>

3.3 Evolution process of interflow
The simulated results presented in the above sections illustrate the impact of inflow conditions on the formation of density current under the thermal stratification state. However, the density currents could evolve with the passage of time, the pattern and features of density currents would vary with time as well, and this in turn would influence the pollutant transport. In order
to understand the actual impact of interflow on the operation of lakes and reservoirs, the evolution of density flow in the stratified waters was numerically investigated and was shown in Fig. 6.

Fig. 6 Evolution process of interflow

From Fig. 6, the evolution process of interflow can be classified as four principal stages. The first stage is the beginning of interflow, which the water is stably stratified. When the inflow went beyond the thermocline layer, the flow pattern is the traditional undercurrent. The second stage is the formation process of interflow. According to the analysis in the previous sections, the temperature difference would produce the internal hydraulic jump while the header flow went into the thermocline. And the third stage is the process after forming of interflow. With the increased water volume from inflow, the mixed water could spread to the surface of water body, which can pollute the water. The last of stage is the diffusion process. The pollutants from the turbid inflow could entirely diffuse in the surface water area, and this will increase the pollution load in the reservoirs and lakes under certain conditions.

4. CONCLUSIONS

(1) Simulated vector profiles using Euler-Euler model agreed well with the experimental data obtained in a pilot stratified reservoir. Under thermal stratification conditions, the temperature gradient influenced the patterns of the density currents, the weaker the stratification, the lower the separation depth. Muddy sediment may even produce interflow separation outside the thermocline layer.

(2) Both inflow velocity and sediment content of inflow influence the propagation of density currents under stratified conditions, but in different ways. When the volume fraction of sediment in the inflow was increased from 0.025% to 0.20%, the separation depth of density currents decreased from 21.0cm to 18.5cm, the thickness of the interflow slightly increased from 6.2cm to 7.8cm, but the heights of the internal hydraulic jump were almost the same. The inflow velocity mainly influenced the time of developing the interflow, the developing time decreased with the inflow velocity implying the water quality would deteriorate quickly after a heavy rainfall.

(3) Under larger inflow velocity conditions, stronger mixing between the inflow and background water will cause larger depth of interflow and the bigger height of internal hydraulic jump, which indicated the pollutants carried by turbid inflow would be transported more widely.

References:


