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Numerical characteristics study on Delft3D for simulating the density flow caused by temperature difference in a reservoir flume

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ABSTRACT

Modeling researches on hydrodynamic and temperature characteristics of tributaries of Three Gorges Reservoir (TGR) are generally employed the two-dimensional model of the lateral-averaged N-S equation. In order to obtain a detailed hydrodynamic process, it is necessary to establish a three-dimensional (3D) model. Delft3D (D3D), a widely used software, was utilized to study this issue. Firstly, based on the classical physical model test results conducted by Johnson et al., the numerical characteristics of D3D software in simulating temperature stratified density flow are studied. The σ and z coordinates are compared and analyzed on bed slope and vertical stratification. It found that the coordinate system and the scale of the model mesh in all directions have a impact on the results. The influence of σ and z coordinate system on the result is most related to the longitudinal slope of the river bottom. Considering the characteristics of the change of the Xiangxi River (XXR) bottom and the significant temperature stratification of the internal water body, it is recommended to establish the 3D numerical model of XXR-TGR system by the z-coordinate.

Keywords: Three Gorges Reservoir, temperature stratified flow, Delft3d, z-coordinate

1. INTRODUCTION

Since the impoundment of the Three Gorges Reservoir (TGR), water blooms have occurred in several tributaries, and it has been aroused public concern (Yang et al., 2010). Some studies have shown that one of the main causes of these phenomena is the change in hydrodynamic characteristics in these bays (Yang et al., 2017). Xiangxi River (XXR), the nearest tributary from the Three Gorges Dam, has typical significance to study this problem (Cai et al., 2006). The results of previous field observations and numerical simulations show that the hydrodynamic process in the vicinity of the junction of XXR and the Yangtze River provides a source of pollutants and suitable hydrodynamic conditions for algal blooms (Liu et al., 2012). Therefore, obtaining detailed hydrodynamic characteristics at the combining region of reservoirs and tributaries is of great significance to explain the mechanism of reservoir tributary bloom. Building a three-dimensional (3D) numerical model of hydrodynamics and water temperature is very meaningful and economical. Delft3D (D3D), a widely used software, was utilized to study this issue.

Generally, there are two vertical coordinate type to construct a three dimensional model of D3D, one is z-coordinate, the other is σ-coordinate (Cornelissen et al. 2004). For steady-state temperature stratified region, the isothermal tends to be horizontal, so as the density flow direction. The z-coordinate mode can be used in this condition. For the bottom descending density flows induced by temperature stratification, however, the direction of water flow may change along the bed surface (bottom density current). Thus the temperature stratification is not horizontal, and the z-coordinate model may not applicable. The σ-coordinate mode can fit the changes of the free surface and the terrain of the bed in this condition. However, it may cause the calculation error of the horizontal baroclinic gradient force in the steep slope region (Haney, 1991). The existing improvement methods of D3D such as anti-creep correction (Stelling et al., 1994) and bottom grid redistribution (Platzek et al., 2012) cannot completely quantitatively eliminate this error. Therefore, how to choose a suitable vertical coordinate system in the simulation of temperature stratified density flow in reservoir bay is still need a specific study for specific problem.

In this study, based on the physical model experiments conducted by Johnson (1981), different types of vertical grid coordinate were employed to establish the numerical models using D3D software. By comparing the modeling results, general suggestions on coordinate selection for simulating reservoir bay temperature stratified density flow using D3D model are given. According to the terrain and hydrodynamic characteristics of the XXR, suitable advises for establishing a 3D model of the XXR using D3D is proposed.

2. Materials and methods

The D3D model was developed by the Dutch institute for Delta Technology (Deltares) and can be used to simulate three dimensional (3D) currents, waves, water quality, ecology, sediment, etc. The governing equation is the incompressible fluid N-S equation based on the shallow water assumption and Boussinesq assumption, the vertical acceleration is ignored in the vertical momentum equation. The vertical flow velocity of the 3D model is obtained from the continuous equation. In the earlier version of the model, an orthogonal curved mesh was used in the horizontal direction, and in recent years, a non-structured mesh version (D3D Flexible Mesh) appeared. In the vertical direction, two modes of σ-coordinate system and z-coordinate system can be utilized. An anti-creep correction is given for the vertical false mixing problem that may occur when the σ-coordinate system has a large slope at the bottom. Aiming at the step approximation of the z-coordinate at the bottom boundary, a method of bottom grid redistribution was also proposed (Hydraulics, D., 2019).

Considering the various uncertainties of the field observation results, Johnson (1981) conducted an experiment about cold water submerging into the narrow reservoir on the Generalized Reservoir Hydrodynamics (GRH) water tank of the Waterways Experiment Station (WES). The temperature and basic hydrodynamic data were obtained. Sketch of the experiment tank is shown in Figure 1. Its length is 24.39 m, the downstream section size is 0.91 m × 0.91 m, and the upstream section size is 0.30 m × 0.30 m. The water tank can be divided into two sections. The upstream section is 6.10 m in length, 0.30 m in depth, and the width changes linearly from 0.30 m to 0.91 m. The downstream section is 18.29 m in length, 0.91 m in width, and linearly changes from 0.30 m to 0.91 m in depth. At the initial moment, the model reservoir is in a stationary and uniform state with a water temperature of 21.44 ℃. During the experiment, cold water at 16.67 ℃ was introduced from 0.46 m from the upstream section, and the baffle restricted cold water from entering 0.15 m above the bottom. The inflow and outflow discharge are both 0.00063 m^3/s. The downstream section is an orifice with a diameter of 2.54 cm, 0.15 m from the bottom and in the middle of the section.

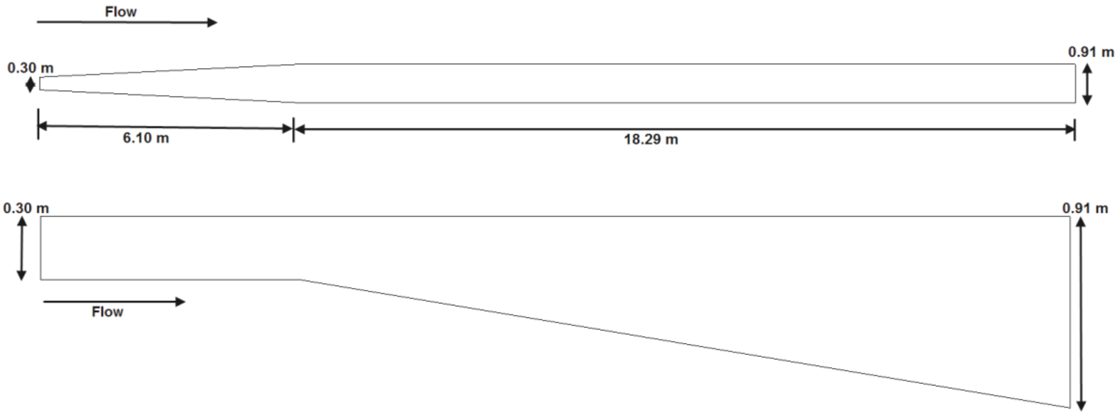


Figure 1. Sketch of the Generalized Reservoir Hydrodynamics (GRH) water tank of the experiment

In this experiment, the isothermal surface and the vertical grid interface of the σ-coordinate model are relatively close. Therefore, the model using the σ-coordinate should have higher accuracy than the z-coordinate model. The horizontal baroclinic gradient force problem of σ-coordinate model is not significant in this condition. For comparison, numerical models of σ and z coordinates were both established using D3D. Details of simulation conditions can be seen in Table1. The grid scale ratio for longitudinal to horizontal is 3:1, and it has validated before we conduct this investigation. Due to space limitations, these contents will not be explained in this paper. The longitudinal, horizontal and vertical grid number of the two models are the same, so are the model parameters.

D3D software can improve the accuracy caused by step approximation in the z-coordinate model through bottom grid redistribution (Hydraulics, D., 2019). The grid redistribution result of this study is shown in figure 2.

Table 1. Settings of σ-coordinate and z-coordinate model.

Simulation conditions		σ-coordinate	z-coordinate
Plane grid	Longitudinal/horizontal scale ratio	3:1	
	Longitudinal grid number	80	
	Horizontal grid number	9	
Vertical grid parameters		36	
	Manning number（$m^{-1/3}s$）	0.009	
	Background horizontal eddy viscosity coefficient（m^2/s）	0.01	
	Background horizontal eddy diffusion coefficient（m^2/s）	0.01	
Turbulence model		Constant model	

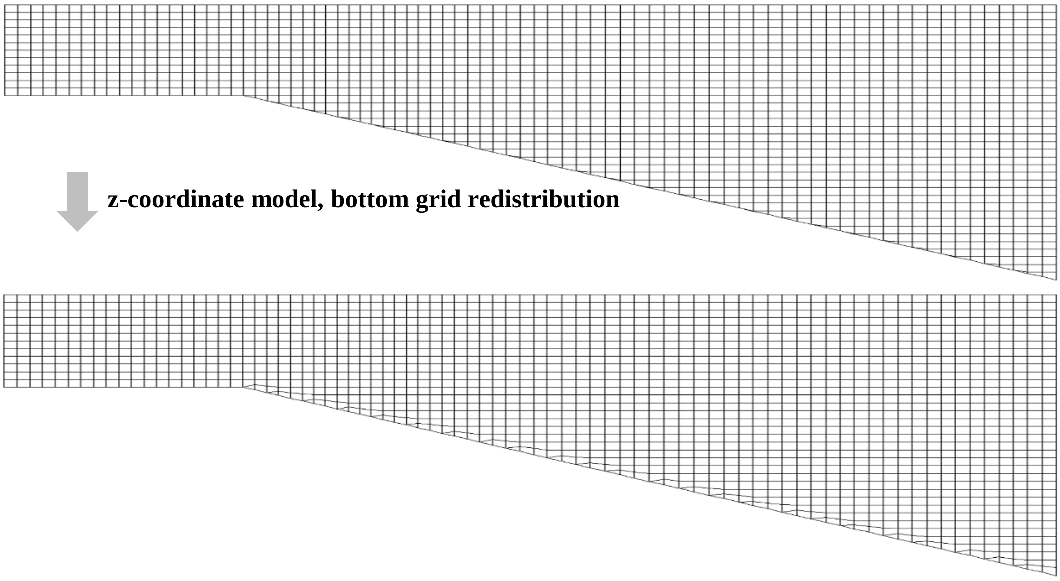


Figure 2. Sketch of bottom grid redistribution in z-coordinate model.

Generally speaking, increasing the vertical grid number can improve the accuracy of the cold submerged current flow in the z-coordinate model. Three simulation cases with different vertical grid number are designed as shown in Table 2.

Table 2. Simulation cases with different numbers of vertical grids based on z-coordinates

Simulation cases		B1	B2	B3
Plane grid	Longitudinal grid number		80	
	Horizontal grid number		9	
Vertical grid number		36	72	100

Considering that the influence of the bottom slope on the simulation accuracy of different vertical coordinate systems is very significant, five types of cases for the bottom slope from 1‰ to 5‰ are simulated for this study. Other parameters can be seen in Table 3. Each ratio of the height of the water outlet to the height of outlet section is in consistent with the physical experiment conducted by Johnson et al.

Table 3. Simulation cases set up to study the influence of bottom slopes in different coordinate systems on results of density flow characteristics.

Simulation cases	C1	C2	C3	C4	C5
Bottom slop	1‰	2‰	3‰	4‰	5‰
Water depth in front of the downstream boundary（m）	0.318	0.337	0.355	0.373	0.392
Height of the downstream outflow（m）	0.053	0.056	0.059	0.062	0.065

3. RESULTS

3.1 Comparison of σ-coordinate and z-coordinate

Water temperature at the outlet of different vertical coordinate system models over time are shown in the Figure 3. Vertical velocity distribution at 11.43 m upstream at t = 11 min of different coordinate are shown in Figure 4. From Fig. 3 to Fig. 4, it can be known that the calculation results of the z-coordinate system reservoir model have large deviations from the observed values. The improved method of bottom grid redistribution has less influence on the outlet water temperature, only reduces the speed near the bottom, but does not affect the overall vertical velocity distribution.

According to Figure 3, the time when the outlet water temperature starts to fall is t = 15 min, and the time when the outlet water temperature calculated by the z coordinate model starts to fall is t = 24 min, which is 9 minutes later than the observed value. At the end of the z-coordinate model, the outlet water temperature is also much higher than the observed value. According to Figure 4, the thickness of the submerged density current in cold water is 0.12 m, while the thickness of which in the z-coordinate model is about 0.24 m. Moreover, the reverse velocity of the upper layer is also significantly larger than the observed value, which indicates that the vertical velocity gradient of the z-coordinate model is small, which causes the speed of the submerged cold water to be small, while the reverse velocity of the upper layer is increased.

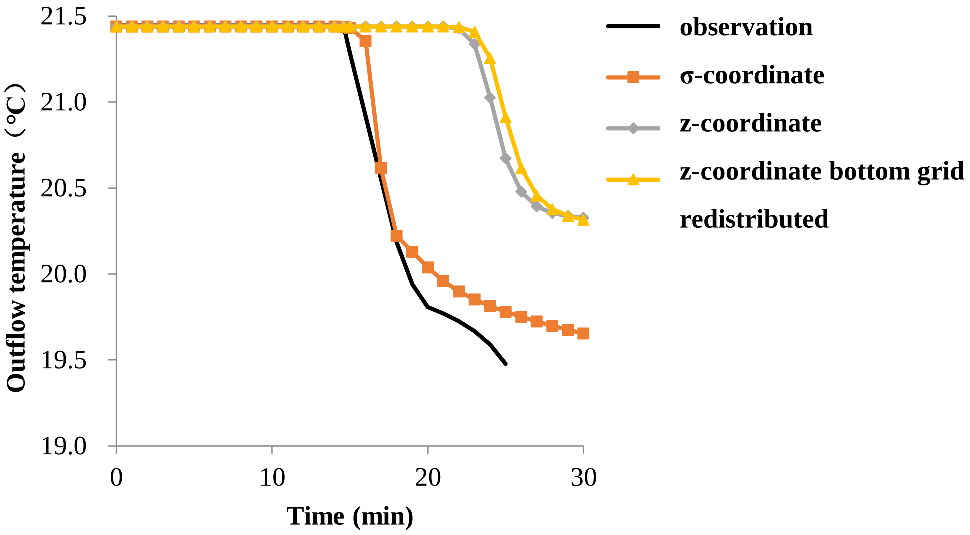


Figure 3. Water temperature change at the outlet over time of different vertical coordinate models.

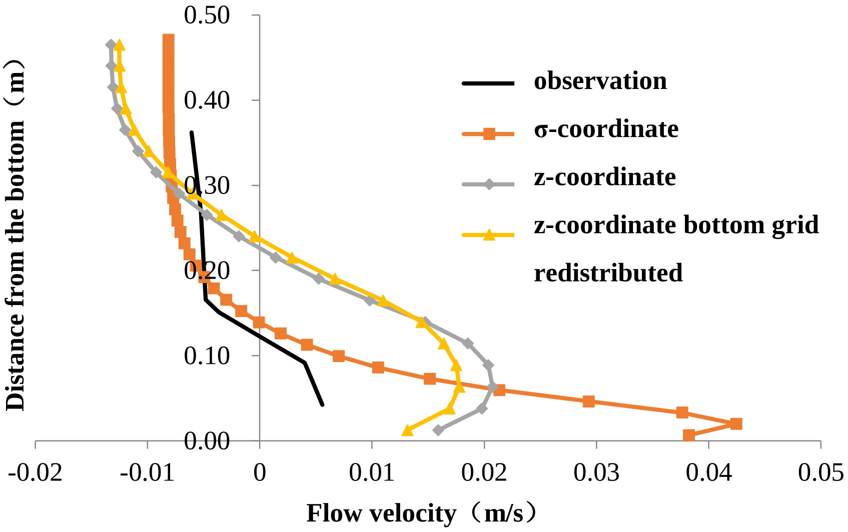
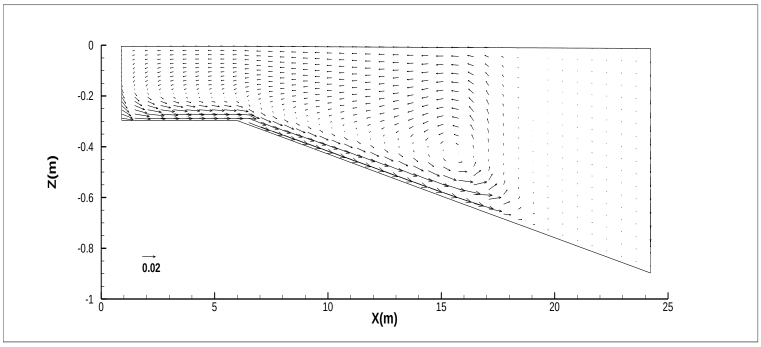
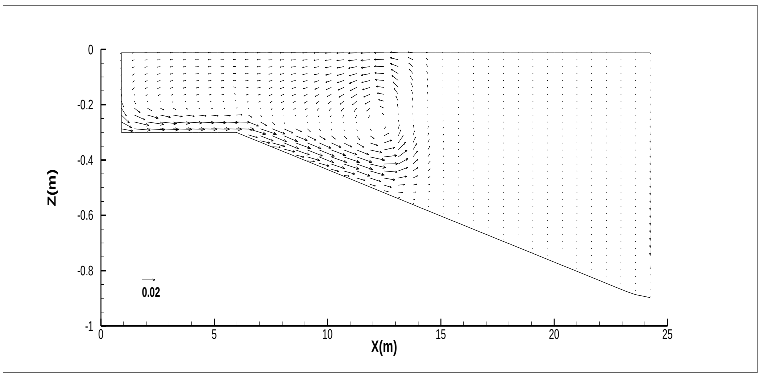


Figure 4. Vertical velocity distribution at 11.43 m upstream at t = 11 min of different coordinate models.

Central longitudinal velocity distribution of the flume when t = 12 min with different vertical coordinate are shown in Figure 5. It can be seen that the submerged distance of bottom cold water with σ-coordinate is great than with the z-coordinate. There is a fundamental difference between the mixing process of σ coordinate model and z coordinate model, which may be the main reason for the difference in simulation results. In the σ-coordinate model, the pressure gradient driven convection along the σ-coordinate face. In the z-coordinate model, the process of cold water diving down the slope can be divided into two steps. First, horizontal convection and diffusion causes cold water to mix with adjacent horizontal grid cells, which cover the lower grid cells with a slightly greater density. Then, because the unstable stratification causes strong vertical mixing, the flow velocity of the z coordinate model decreases.



（a） σ-coordinate



（b） z-coordinate

Figure 5. Central longitudinal velocity distribution of the flume when t = 12 min.

3.2 Effect of vertical grid number on z-coordinate model

According to Figure 6, with the increase of the number of vertical grids, the time at which the outlet water temperature starts to fall is slightly delayed, but the outlet water temperature at the final time is nearly unchanged. Generally speaking, the effect of increasing the vertical grid on the outlet water temperature is small. According to Figure 6, with the increase of the number of vertical grids, the speed of the submerged flow in cold water decreases, while the speed of the reverse flow in the upper layer decreases slightly. In general, increasing the vertical grid number does not evidently affect the vertical distribution of the velocity, and the thickness of the submerged current in cold water remains changed slightly.

It can be known from Fig. 6 ~ Fig. 7 that after the vertical grid number is increased, the calculation result of the z-coordinate system reservoir model still has a large deviation from the observed value. It can be concluded that the vertical grid resolution is important to accurately simulate the cold submerged flow of the reservoir, but it is not the main cause of the calculation errors of the z-coordinate reservoir model.

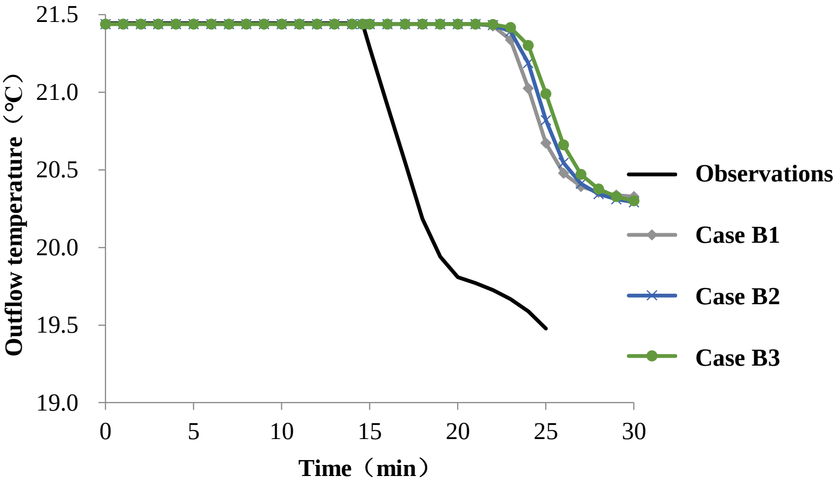


Figure 6. Water temperature at the outlet of z-coordinate model with different vertical grid numbers

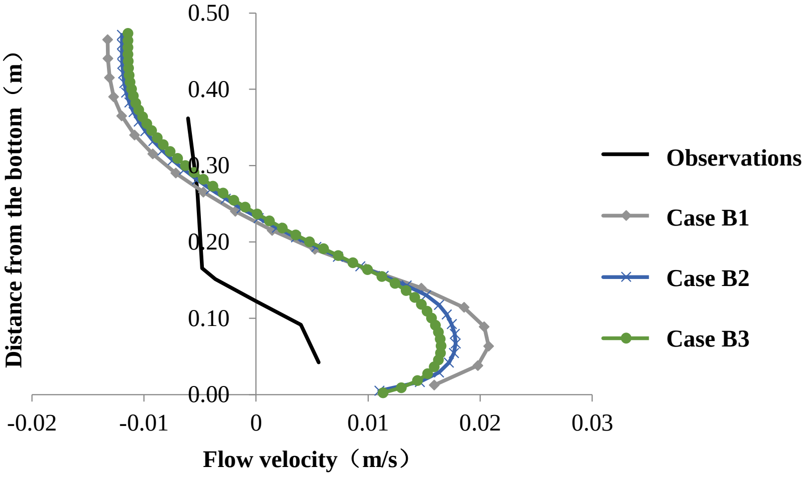


Figure 7. Vertical velocity distribution at 11.43 m upstream at t = 11 min of z-coordinate model with different vertical grid numbers.

3.3 Relationship between vertical coordinate and bottom slope

As can be seen from Figure 8, when the slope of the reservoir is small (C1 ~ C2), the calculation result of the z-coordinate is basically consistent with the σ-coordinate; as the slope of the reservoir gradually increases, the deviation of the calculated results from the two coordinate models also gradually increases. This shows that when the slope of the reservoir is small, the z-coordinate grid model can also be used to simulate cold submerged density currents. Following characteristics of the outlet water temperature (t = 20 ~ 30 min) can be summarized.

(1) Under the same bottom slope, the outlet water temperature value calculated by the σ-coordinate model is always lower than the calculation result of the z-coordinate model. This means the vertical diffusion calculated by the z-coordinate reservoir model is larger, which leads to a high outlet water temperature.

(2) In the σ-coordinate model, with the increase of the slope, the outlet water temperature at the same time gradually decreases. This means when the bottom slope of the reservoir is larger, the speed of the submerged cold water is faster, so the outlet water temperature is also decreased more quickly.

(3) In the z-coordinate reservoir model, for cases C1 ~ C3 (bottom slope ≤ 3 ‰), as the slope gradually increases, the outflow water temperature at the same time gradually decreases; for cases C4 ~ C5 (bottom slope ≥ 4 ‰), the outlet water temperature at the same time tends to be approximate. This means that when the bottom slope is larger than 4 ‰, the simulation results of the z-coordinate model are affected by the step approximation, resulting in a large calculation error, and the error also increases as the bottom slope increases.

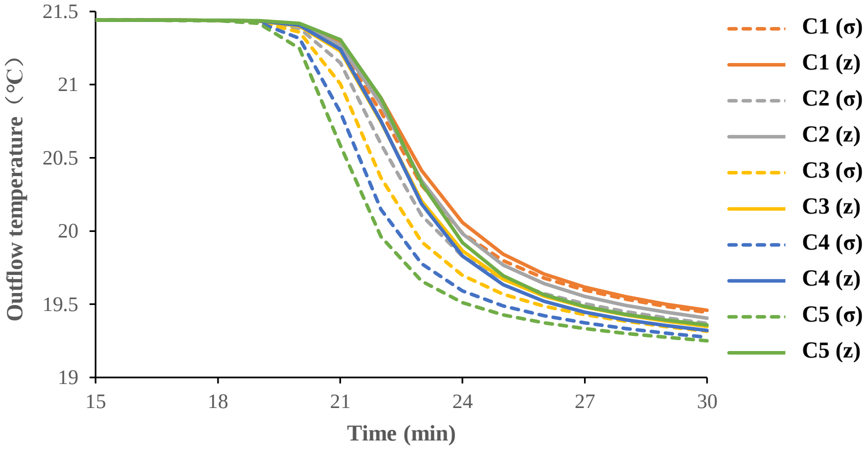


Figure 8. Comparison results of σ-coordinate and z-coordinate model outlet water temperature under different bottom slope conditions.

4. DISCUSSION

We find that for temperature induced density currents along the bottom of the reservoir, when the model with σ-coordinate is close to the flow direction, it will has more accuracy than the z-coordinate model. However, the density flow in combining region of the XXR and Yangtze River is very complicated. There are different density currents at the bottom, at the middle layer, and sometimes form the vertical circulations (Holbach et al., 2014). Considering that the isothermal surface modeling results in upper layer of σ-coordinate model may change with the terrain at the bottom of the reservoir (Yu et al., 2013), the use of σ-coordinates to study temperature induced density flow in actual reservoirs requires careful consideration. For these reasons, the z-coordinate model is still the preferred model, but when the bottom slope is large, special attention must be paid to the error caused by the bottom step approximation. This error can be reduced by increasing the number of layers, but the effect is not obvious. Moreover, the influence of the slope of the reservoir bottom on the simulation accuracy is significantly greater than that of the grid scale and the number of vertical grid intensity.

It is generally believed that the starting point for investigating the hydrodynamic characteristics of temperature stratified current in the XXR is Gaoyang Town, about 32km away from the river mouth (Dai et al., 2013). The average slope of this river reaches between 2.0 ‰ and 2.5 ‰. According to the results of this study, when the bottom slope is less than 3 ‰, both the σ-coordinate and the z-coordinated model based on D3D software can better simulate hydrodynamic and water temperature characteristics of bottom submerged density flow. Therefore, it is recommended to use the z-coordinate in vertical direction when establishing the numerical model of XXR with D3D software.

5. CONCLUSIONS

This study shows that when D3D software is used to simulate submerged density currents in a reservoir, the selection of the vertical coordinate system has a large impact on the accuracy of the simulation. When the density currents is along the bottom slope of the reservoir, the model accuracy using the σ-coordinate is obviously better than the model using the z-coordinate, but as the bottom slope becomes flat, the gap gradually decreases. When the slope is less than 3 ‰, the difference between the two vertical coordinate systems becomes very small. For the model adopting the z-coordinate in the vertical direction, changing the size and number of the plane and the vertical grid has little effect on the calculation results. The effect of the bottom grid redistribution proposed in D3D software on the simulation results is also small. According to the bottom slope data of the XXR, the average bottom slope is between 2‰ and 2.5 ‰. Therefore, a vertical z-coordinate model can meet the requirements of simulating the density current along the river bed in the XXR, and can avoid the calculation error caused by the barometric pressure gradient force of the σ-coordinate coordinate model. This conclusion can also be utilized to other stratified water bodies with bottom slopes less than 3‰.

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