Simulation research on hydraulic characteristics of conical X-shaped flaring gate piers in lock chamber based on CLSVOF method

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Abstract. 3-D numerical simulation was carried out for flood discharge and energy dissipation process of conical X-shaped flaring gate piers in a hydropower project by using coupled Level Set and VOF method and RNG k-ε turbulent model. The change laws of flow pattern, water surface profile, velocities and pressures distributions in lock chamber of conical X-shaped flaring gate piers were gained. The results of numerical simulation were compared with the model test data and good agreement was found. The numerical results show that, there are differences on both of water surface profiles in lock chamber. With the increase of discharge, water surface profiles falls at the longitudinal axis and vertical diffusion of ski-jump flows are large on the downstream of flaring gate piers.

1. Introduction
X-shaped flaring gate piers have been widely used in engineering practice in recent years, which mainly used in high-head large single-width power stations, and combined with the step overflow surface behind the dam to discharge and dissipate energy. The water flow was fully diffused in the air by the action of the flaring gate piers, mixed with a large amount of gas, and fell into the stilling pool after the water tongue, a three-dimensional turbulent flow was formed in the stilling pool, which increased the energy dissipation effect and can shorten the length of the pool. So it has its unique advantages in energy dissipation effect. In recent years, many scholars have carried out research on the design and improvement of the flaring gate piers. Due to the complex shape and hydraulic elements such as free water surface under its action are much more complicated than conventional hydraulic structures, the design and optimization of the flaring gate pier mainly rely on model experiments at present.

Numerical simulation is an important research approach to hydraulic problems, and some scholars have also achieved certain results in numerical simulation of the hydraulic characteristics of the flaring gate piers. However, the numerical simulation technology has the shortcomings of low accuracy while simulating the flow field characteristics of hydraulic structures, and there are certain errors between the simulation results and the model experiments. On the basis of summarizing previous experience, 3-D numerical simulation was carried out for flood discharge and energy dissipation process of conical X-shaped flaring gate piers in a hydropower project by using coupled Level Set and VOF method and RNG k-ε turbulent model. The change laws of flow pattern, water surface profile, velocities and pressures distributions in lock chamber of conical X-shaped flaring gate piers were gained. The reliability of the numerical simulation method is verified by the model experiment results.
2. Discrete area and calculation conditions
The upper surface of the conventional X-shaped flaring gate pier is flat, the curved X-shaped flaring gate pier optimizes the upper surface of the conventional stiletto pier into a conical curved surface, which can make the water flow in the lock chamber smoother, and stretch longitudinally the water flows when it running out of the lock chamber at the same time, which can make the water flow more fully aerated by diffusing the upper part of the water flow.

In order to facilitate the comparison with the model test data, the calculation area in this paper includes the reservoir, the gate chamber section of the X-shaped flaring gate pier, the platform stage and the stilling pool section. Due to the complex boundary of the X-shaped flaring gate pier, the whole calculation area is divided by a hybrid method of structured and unstructured grids. The grids in the calculation domain are combined with different density according to the different areas. The number of grids is 1.2 million. The calculation area is 113m high, 108m wide and 270m long.

There are five spillway holes in curved X-shaped flaring gate pier in the calculation domain. According to the symmetry of the flow, the two sides of the simulation calculation are defined as symmetrical boundary conditions. The upstream is given the reservoir water level, the upper part of the reservoir and the water tongue are defined as pressure inlet. The outlet are defined as pressure outlet with limit water level. All walls are defined as non-slip boundary conditions. The viscous bottom layer is treated by wall function method. The whole field is a transient simulation. The inlet and outlet flow error is within 5% When the calculation is considered stable.

3. Numerical simulation results and analysis
The numerical simulation shows the velocity vector distribution diagram behind the curved X-tail pier. It can be seen that the cross-sectional velocity distribution is very chaotic after the water flows out of the lock chamber, which makes the water easier to entrain a large amount of air, increases the water-air mixing effect, and improves the energy dissipation effect.

Figure 3 and Figure 4 respectively show the water surface line distribution on the left and right sides of the lock chamber and floor pressure distribution. The numerical simulation results are compared and verified with the left water surface line and floor pressure distribution measured by the model experiment. It can be seen that numerical simulation results are in good agreement with the model experiment results, which shows that the CLSVOF method can be applied to the simulation of turbulence problems with complex free water surfaces, and the calculation results can guarantee certain accuracy requirements, which verifies the reliability of the method.

Figure 3(a) shows the flow rate Q=12766m3/s. It can be seen that when the section x=-100m~96m, there are small areas of stagnation on the both sides of the water surface. In the range of x=-96m~76m, the water surface line on the left and right sides experienced a low left and high right, the height difference between the two sides is increased and then decreased. When x=-76m, the water surface height difference between the left and right sides is 0, where the water surfaces on both sides of the lock chamber are in the same level; when x=-76m~56m, the left and right water surface lines experience a
left high and right low, the height difference is always increasing. The distribution of the water surface lines on both sides of the lock chamber shows that \( x = -76 \text{m} \) is the dividing point, there are two torsion surfaces, and the two torsion surfaces twist in opposite directions.

As shown in Figure 3(b), the flow rate \( Q = 15554 \text{m}^3/\text{s} \). From the distribution of water surface line on both sides of the lock chamber, it can be seen that there are also two twisted surfaces in the lock chamber with opposite twisting directions, but the difference from Figure 3(a) is that the point where the water level difference on both sides is 0 appears at \( X = -78 \text{m} \).

It can be concluded that under the action of the conical X-shaped flaring gate pier, the water flow on both sides of the lock chamber no longer remains flush, but appears different twisting states: the left is low and the right is high in the first half of the lock chamber, and the left is high and the right is low in the second half of the lock chamber. The greater the incoming flow, the closer to the entrance of the lock chamber where the water surface lines on the left and right sides of the lock chamber are flush.

![Figure 3](image3.png)

**Figure 3.** The comparison of water surface profiles in lock chamber

![Figure 4](image4.png)

**Figure 4.** The comparison of bottom pressures in lock chamber

Figure 5 shows the velocity distribution along the way in the lock chamber at a height of 3m from the surface of the overflow weir. It can be seen from the figure that after the water flow enters the lock chamber, the flow velocity begins to increase. Near the middle of the lock chamber, affected by the width of the pier at the rear, the flow velocity increases slowly, and the flow velocity curve is close to horizontal. After the middle of the conical X-shaped flaring gate pier, the flow rate began to increase rapidly until it reached the exit. For conditions with large flow, the flow velocity along the way is greater than small flow.
Figure 5. The comparison of velocities in lock chamber

4. Conclusion
3-D numerical simulation was carried out for flood discharge and energy dissipation process of conical X-shaped flaring gate piers in a hydropower project by using coupled Level Set and VOF method and RNG k-ε turbulent model. The reliability of the simulation method is verified by comparing with the experimental results of the model, which shows that it can numerically simulate and calculate the flow field motion problem with complex free water surface, and it has a wider application prospect in the complex water flow simulation calculation.

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