Study on the disruption of water flow in the system of tailrace tunnel combined with diversion tunnel

LI Ling¹, YANG Jiandong¹, LIU Meiqing²
1. State Key Laboratory of Water Resources and Hydropower Engineering science, Wuhan University, Wuhan 430072, China; 2. School of Power and Mechanical Engineering, Wuhan University, Wuhan 430072, China

E-mail: liling7@whu.edu.cn, jdyang@whu.edu.cn, liumq@126.com

Abstract. In order to solve the space-intensive problems of large-scale underground hydropower stations, diversion tunnel is usually used as the end part of the tailrace tunnel and connected with the front one by an abrupt slope. However, shallow water depth and large velocity happened at the slope. And the disruption of water flow even probably happened after the unit load rejection. According to CFD numerical calculations of the transition process, the mechanism of water flow disruption was analysed in this paper and the main conclusion is drawn on that Froude number Fr at the slope, especially the end section of the slope, is smaller than 1 at first, increased to 1 and then greater in the transient process. The formation of wave breaking blocked the supply of the reverse flow. In this way, Fr>1 can be regarded as the internal cause of disruption. Furthermore, the water depth at the combined point was lowered by the increasing water level of the surge tank. Inevitably, the disruption would occur when the water level of the surge tank is rising.

1. Introduction

With the continuous investment in the construction of many large underground hydropower stations in southwest China, in order to solve the space-intensive problem of underground cavern, diversion tunnel is usually used as the end part of the tailrace tunnel and connected with the front one by an abrupt slope. The typical layout of such system is usually consists of three parts: I, front tailrace tunnel; II, diversion tunnel and III, the connecting slope, as shown in Figure 1. For the following analysis, the end section of the slope is defined here as connecting section of front tailrace tunnel and diversion tunnel.

Figure 1. Profile of a hydropower diversion system
Due to the different functions of tailrace and diversion tunnel, the bottom elevation of latter is usually relatively high and the bottom slope is more gently, needs a slope with large inclination to combine with the front tailrace tunnel. So when the downstream water level is low, free surface-pressurized flow would happen in the whole tailrace system. The water depth in the diversion tunnel is shallow and flow velocity is large. The value of Froude number $F_r = \frac{v}{\sqrt{gh}}$ would be close to 1 or bigger initially. During the transient process of load rejection condition, the flow velocity would getting larger and larger, equal or even greater than gravity wave velocity, resulting in the appearance of breaking wave or flow disruption and the gravity wave only propagating downstream. Through a three-dimensional numerical CFD model of the whole tailrace system, the mechanism of breaking wave or even disruption of flow was evidently obtained.

Take a hydropower station under construction for example, with the arrangement of two machines using one tailrace tunnel, the unit capacity is 1000MW; rated water head is 202.0m; rated flow is $547.8 m^3/s$; the bottom elevation of front and end section of slope are 559.0m and 574.0m respectively. The cross-sectional dimensions of surge tank, front tailrace tunnel and diversion tunnel are shown in Figure 2.

Calculation condition: The two units rejected full loads when the downstream water level is 582.14m (two machines generating tail water level).

![Figure 2. Cross-sectional dimensions of surge tank, front tailrace tunnel and diversion tunnel](image)

### 2. Simulation models

As seen from Figure 3, the calculation region is from the outlet of draft tube to the downstream. And the boundary conditions: 1) inlet: time-varying process of outlet flow of draft tube (As seen from Figure 4, obtained by one-dimensional transition process simulation); 2) outlet: a known constant water level; 3) surge tank, gate chamber and vent holes: the atmospheric pressure at the top. The mathematical model: 1) Multiphase flow model using VOF; 2) Second-order realizable $k-\varepsilon$ turbulence model; 3) near the wall using a standard wall functions; 4) discrete finite volume method for incompressible NS equations; 5) pressure-velocity coupling using PISO algorithm applied to unsteady flow calculation.
3. Results and analysis

Calculated using the three-dimensional CFD model shown in Figure 3, the water disrupting phenomenon was observed during the transient process.

3.1. Flow pattern of typical moments

Water surface at the connecting slope of five typical moments are shown in Figure 5 to 9, described the special flow phenomenon such as free surface-pressurized flow, water disrupting, air bags, bubbles, etc. And the corresponding flow velocity vector distributions are shown in Figure 10 to 13, recorded the process of the water disrupting.

Figure 3. Three-dimensional calculation model

Figure 4. Time-varying process of outlet flow of draft tube

Figure 5. Profile and layout of water surface at initial moment, the initial interface of free surface-pressurized flow was at the slope (t=0.00s).

Figure 6. After load rejection, the water depth decreased gradually and the length of the free flow became longer (t=94.62s).
Figure 7. With the formation of the breaking waves and the water into the surge tank, disruption of water flow happened at the combined point (t=106.22s).

Figure 8. Then with the flow out of the surge tank, intermittent bubbles showed at the above of tailrace tunnel (t=158.39s).

Figure 9. A small wave occurred in the tailrace tunnel and moved to the downstream (t=176.08s).

Figure 10. Flow velocity vector distribution (t=67.82s) (Balck line represents the water surface line)

Figure 11. Flow velocity vector distribution (t=88.25s)
3.2. Time-varying process of character parameters

Figure 12. Flow velocity vector distribution (t=102.55s)

Figure 13. Flow velocity vector distribution (t=135.72s)

Figure 14. Time-varying process of length of the free flow

Figure 15. Time-varying process of water depth

Figure 16. Time-varying process of discharge

Figure 17. Time-varying process of Fr
Based on the analysis of interrelationship of above parameters, the mechanism of water flow disruption in the tailrace system was revealed. However, the whole unit load rejection transient process can be divided into three stages: I, the breaking wave formation period (from initial constant moment to load rejection); II, breaking wave propagation process; III, period of bubbles generated and discharged in the tailrace tunnel. A detailed analysis of each parameter changing process during the three stage is as follows:

1) T=0.00~88.25s, at the initial time t=0.00, the interface of free surface-pressurized flow was about 350m to the outlet of downstream. And with unit load rejection, the unit discharge gradually decreased to 0 within 14 seconds, leaving the free flow surface back water waves. However, at the former 82.66s, the interface of free surface-pressurized flow moved to the front tailrace tunnel slowly, as 422.71m (seen from Figure 14). The reason is that during the time, water was outflowing from the surge tank to the front tailrace tunnel (seen from Figure 19). And the entire flow of tailrace tunnel moved positively.

2) T=88.25~135.72s, then because of the water pressure between downstream and surge tank water level, the flow in the front tailrace tunnel began to move at a reversed direction till t=88.25s (seen from Figure 17). Then with the inflow of surge tank, the interface of free surface-pressurized flow rapidly moved to the front tailrace tunnel, as 213.1m from t=82.66s to t=137.75s (seen from Figure 14). And during this time, the water disruption phenomenon happened at t=102.55s, the corresponding value of Fr was -2.81 (seen from Figure 17). The water level was 1.21m (seen from Figure 15). And the flow discharge was -61.05m³/s (seen from Figure 16). However, breaking wave propagation process lasted about 33.17 seconds. It occurred at the end of t=135.72s, and the water level was lowest 0.79m. During the 33.17 seconds, the flow in the tailrace tunnel was moving conversely (seen from Figure 16). And from t=67.82s to 151.89s, the flow moved into the surge tank. Interestingly, the time of maximum discharge into the surge tank was almost the same time when the water disruption appeared (seen from Figure 19). Therefore, we can say that the most direct reason for water disruption phenomenon was that the reverse flow in the tailrace tunnel cannot meet the demand of the maximum discharge into the surge tank. And the ending of the breaking wave transfer process was caused by the gradually decreasing into flow of surge tank. The reverse flow at downstream of the disruption was greater than the upstream.

3) After t=135.72s, with the water again flowing out of the surge tank, the interface of free surface-pressurized flow moved to the outlet of downstream. It can be seen from Figure 14: the location of interface mutated about 300m to the downstream within a few seconds, which indicated the formation of large air bags.
4. Conclusions
According to CFD numerical calculations of the transition process, the mechanism of water flow disruption in the system of tailrace tunnel combined with diversion tunnel was analysed in this paper and the main conclusion are as follows:
1) When the downstream water level is low and after the unit load rejection, the value of Fr at the connecting slope would increase to 1 and then greater in the transient process. The formation of wave breaking blocked the supply of the reverse flow. In this way, Fr>1 can be regarded as the internal cause of disruption.
2) After unit load rejection, tailrace surge tank would experience a process with first drop and a later rise. During the water level rising phase, due to the inertia of water flow, the water in the tailrace tunnel must move into the surge tank, and the water depth in the slope would further decrease. Inevitably, the disruption would occur when the water level of the surge tank is rising. So the setting of tailrace surge tank is another major reason for the water disruption.

5. References
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