Influence of mixed free-surface and pressurized flow on transients process in a tailrace tunnel of a tailrace surge chamber

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Abstract: In the calculation of hydraulic transients in a hydropower station, the hydraulic problems caused by free-surface and pressurized flow are relatively complex. In consideration of this phenomenon, numerical simulation is used in this paper to study the effect of the transient free-surface, pressurized flow in a tailrace tunnel on the minimum pressure at inlet of the draft tube and the lining segment of the tailrace tunnel and the effect on the primary frequency regulation of the unit. The results show that the existence of tailrace surge tank can reduce the disturbance of the mixture flow on the units. Meanwhile, free-surface and pressurized flow can speed up the attenuation of the surge in the surge tank. Reasonable arrangement can mitigate transients in the tailrace system, which may provide a reference for similar projects.

1. Introduction
Many large hydropower stations often convert diversion tunnels into power generation tailrace tunnels in the design to reduce the amount of excavation of rock tunnels and reduce bank slope treatment work, thereby saving a lot of investment. When the tailwater tunnel is longer, the economic benefits of converting the diversion tunnel into a tailwater tunnel are more significant. The bottom elevation of the diversion tunnel is generally designed to be relatively high to meet the requirements of construction diversion, which will inevitably cause the phenomenon of open and full flow when the downstream water level is close to the elevation of the top of the tunnel. Due to its complicated flow pattern, how to accurately simulate the alternating free surface-pressure flow during the transition has always been a difficult problem.

In connection with study of free surface-pressure flow, at present, the most commonly used method is the slit method. The slit method uses the similarity of the physical equations of free surface-pressure flow, add an imaginary slit to the top of the pressurized pipe (Pressman slit), make the pressure flow velocity equal to the open channel surface flow velocity, all other parameters remain unchanged, thus unifying the free surface-pressure alternating flow into a clear flow, effectively avoiding the difficulty of changing the interface between the apparent and fill alternating flows all the time, turn the problem into solving the unsteady flow in the open channel, since this method only requires a set of mathematical equations to be solved, it is convenient to program and easy to use in engineering. This method was first proposed and applied by Priessmann. Cunge and Wegner[1] The Priissmann virtual slit method was supplemented, simulating the alternating flow of apparent and fill. Garcia-Navarro, Capart, Trajkovic, Leon etc.[2-5] are based on the PCW model, using different calculation formats, the free surface-pressure Alternating Flow is simulated and compared with the experiment, and the results are relatively consistent.

Generally, the free surface-pressure Flow phenomenon produced by the diversion system of a
hydropower station during the transitional process of load changes is a rapidly changing pressure alternating process, in this process, large positive and negative pressures will be generated and severe pressure pulsations will be caused. Under the action of this current, Influence on the lining structure of tailrace tunnel, minimum pressure of draft tube inlet under extreme conditions, the operation stability of the unit and the primary frequency regulation performance of the unit will have a certain impact, the tail water surge chamber can effectively alleviate the direct impact of free surface-pressure flow on the operation of the unit, however, free surface-pressure flow has new characteristics. This article is based on the mathematical model of free surface-pressure flow based on the slit method, in conjunction with a large hydropower station under construction in western my country, a study on the free surface-pressure flow hydraulic transition process with a tailwater surge tank was carried out.

2. Mathematical model and numerical method

The momentum equation and the continuity equation describing the unsteady flow in a pressurized pipeline[6-7].

\[
\frac{\partial H}{\partial x} + \frac{V}{g} \frac{\partial V}{\partial x} + \frac{1}{g} \frac{\partial V}{\partial t} + \frac{f}{2gD} \frac{|V|}{V} = 0
\]

(1)

\[
\frac{\partial H}{\partial t} + V \frac{\partial H}{\partial x} + \frac{a^2}{g} \frac{\partial V}{\partial x} + V \sin \theta = 0
\]

(2)

In the formula: \(H\) is the piezometric pipe head, m; \(V\) is the flow velocity in the pipe, m/s; \(a\) is the pressure wave velocity, m/s; \(D\) is the diameter of the pipe, m; \(f\) is the Darcy-Weisibach coefficient; \(g\) is the gravity Acceleration, m\(^2\)/s

The equation describing the gradually changing non-constant free surface flow in a prismatic channel is [6]:

\[
g \frac{\partial y}{\partial x} + V \frac{\partial V}{\partial x} + \frac{\partial y}{\partial t} + g(s - s_0) = 0
\]

(3)

\[
VB \frac{\partial y}{\partial x} + B \frac{\partial y}{\partial t} + A \frac{\partial V}{\partial x} = 0
\]

(4)

\(y\) is the water depth, m; \(V\) is the flow velocity in the open channel, m/s; \(B\) is the water surface width of the open channel, m; \(A\) is the cross-sectional area of the water, m\(^2\); \(s = \frac{n_c^2 V |V|}{R^{1/3}}\), \(s\) is called the energy bottom slope, \(n_c\) is the Manning roughness coefficient, \(R\) is the hydraulic radius; \(s_0\) is the bottom slope of the channel.

The slit method model is shown in Figure 1, the figure uses the similarity of the physical equations of free surface-pressure flow, assume that there is a slit on the top of the pressure pipe, and make the slit width \(B = gA/a^2\), then the unified open flow equations can be used to solve both the open flow and the pressure flow. For unpressurized flow, the pressure calculation result is the water depth of the section, and for pressurized flow, it is the pressure head relative to the bottom of the pipe. From the above assumptions, it can be seen that when the pressure on the interrupted surface of the calculation process is lower than the top of the pipe, the calculation is based on the pressureless flow, and when the pressure on the section is higher than the top of the pipe, the calculation is based on the pressure. For the solution of the mathematical model of free surface-pressure Alternating Flow, First, the basic equations of free surface-pressure flow alternating flow are transformed into standard hyperbolic equations, and then the upwind difference scheme is used for discrete solution[7] to improve the stability of calculation.
3. **Project overview and selection of typical conditions**

The underground powerhouse of a giant hydropower station adopts the first development plan layout, and the layout of the water diversion power generation system on the left and right bank is the same, each is equipped with 8 1000MW Francis turbine generator sets. There are 4 hydraulic units on the left and right banks, and the layout of the water conveyance system is a single-hole, single-machine tailrace tunnel, one-hole and two-machine layout of the diversion tunnel. A total of 8 tailrace tunnels, 5 of them are combined with construction diversion tunnel layout, the other three are dedicated tailrace tunnels. Due to the long tail water tunnel, tail water surge chambers need to be arranged on both the left and right banks; The tailrace tunnel adopts a gentle slope section + steep slope section + flat slope section on the facade. The steep slope section of the tailrace tunnel is about 100m long, The flat slope section is about 586.5m long, the elevation of the exit floor of the tailrace tunnel is 574m, the elevation of the top of the cave is 596m, the layout diagram of the water diversion and power generation system is shown in Figure 2. As the downstream water level changes greatly, under certain water level combinations of the lower reservoir, there will be a full flow phenomenon in the steep slope section and the flat slope section.

![Fig.1 Schematic diagram of slot method](image1)

![Fig.2 Layout diagram of the water division and power generation system](image2)

According to the layout characteristics of the power station, the following typical working conditions are selected according to the characteristics of the minimum pressure at the draft tube inlet under different combinations and the maximum pressure in the open flow section.
Tab.1 Simulation working condition

| Calculation conditions | Upstream water level(m) | Downstream water level (m) | Load change | Description of water level combination and load change | Calculation purpose |
|------------------------|-------------------------|----------------------------|-------------|-----------------------------------------------------|---------------------|
| D1                     | 798.00                  | 582.14                     | 1station →2station →0 | Rated water head, rated output, the power generation water level of the two downstream machines, one machine of the same hydraulic unit runs, one machine is added, and the two machines simultaneously dump the load at the most unfavorable moment | Minimum pressure of draft tube inlet |
| D2                     | 798.00                  | 582.14                     | 2station →1station →0 | Rated water head, rated output, the power generation water level of the two downstream machines, the two machines are operating normally, and successively dump the load at the most unfavorable moment | Minimum pressure of draft tube inlet |
| D3                     | 827.83                  | 625.70                     | 2station →0 | The upstream design flood level (P=0.1%), the downstream check flood level (P=0.1%), two units of the same hydraulic unit simultaneously load off the load, and the guide vanes are normally closed | The maximum internal water pressure in the full flow section (all under pressure) |
| D4                     | 825.00                  | 592.00                     | 2station →0 | The upstream normal water storage level, the downstream cave top elevation, the two units of the same hydraulic unit dump load at the same time, and the guide vanes are normally closed | Maximum internal water pressure in open and full flow section |
| TP1                    | 798.00                  | 582.14                     | / | After the two units add 0.2Hz frequency disturbance for 100s at the same time, add -0.2HZ frequency disturbance at the same time | Bright and full flow conditions, unit stability |
| TP2                    | 804.70                  | 597.42                     | / | After the two units add 0.2Hz frequency disturbance for 100s at the same time, add -0.2HZ frequency disturbance at the same time | All pressure flow conditions, unit stability |

4. The influence of free surface-pressure flow on the minimum pressure of draft tube inlet
During the normal operation of the unit, the open flow section has a strict interface between the free surface flow and the pressure flow. Due to its large flow velocity, the open flow section has a certain effect on the draft tube inlet pressure during the stable operation of the unit. This part adopts three mathematical models for the free surface-pressure flow section, namely: Model 1: The initial free surface-pressure flow boundary is used as a fixed water level boundary; Model 2: The free surface-
pressure flow section is regarded as a pressurized flow; Model 3: Consider the actual free surface-pressure flow process, analyze the influence of free surface-pressure flow on the minimum pressure at the draft tube inlet during the transition process of the power station. The calculation results are shown in Table 2 and Figures 3~4 below:

| condition | Processing method                  | model 1 | model 2 | model 3 |
|-----------|-----------------------------------|---------|---------|---------|
| D1        | Initial pressure of draft tube inlet (m) | 5.08    | 5.16    | 6.55    |
|           | Minimum pressure of draft tube inlet (m) | -5.28   | -5.53   | 0.74    |
| D2        | Initial pressure of draft tube inlet (m) | 5.76    | 5.99    | 9.14    |
|           | Minimum pressure of draft tube inlet (m) | -5.20   | -6.59   | -3.54   |

As shown in Table 2, after considering the free surface-pressure flow (model 3), the initial pressure value of the draft tube inlet is greater than the case where the free surface-pressure flow section is treated as all pressure flow (model 2), this is mainly due to the fact that the flow velocity of the open flow section increases when the same flow rate is considered after the full flow, and the resulting head loss is larger than that of the pressure flow; therefore, when the downstream water level is the same, the initial pressure at the draft tube inlet will increase due to the effect of open full flow. In addition, for the case where the initial pressure at the draft tube inlet under the treatment of all the free surface-pressure flow sections as pressurized flow (model 2) is greater than that under the truncated free surface-pressure flow section (model 1), The main reason is that the boundary of the full flow in model 1 is fixed as the water level boundary, and the influence of the subsequent clear flow section is not considered, therefore, compared with the length of the tailrace tunnel in Model 2, the head loss is smaller. For working condition D1, the unit increases the load first, and dumps all the load at unfavorable moments. The calculation results show that, under this working condition, model 2 is used as all pressure flow treatment, and the minimum pressure at the draft tube inlet is the smallest; When model 3 is adopted, the minimum inlet pressure of the draft tube has been greatly improved when the effect of free surface-pressure flow is considered. The reason is mainly due to the influence of the bright full flow, which slows down the change of the water level in the surge chamber during the start-up process, and reduces the amplitude. Therefore, the initial pressure of the load dump is relatively high. When the load is dumped at unfavorable moments, the minimum pressure at the draft tube inlet has been improved. Improved. For working condition D2, the unit has successive load rejection. Due to the effect of free surface-pressure flow, the reduction of the surge tank water level caused by the first rejection of the unit is reduced. When the second rejection of the unit undergoes load rejection, the initial pressure is relatively high, so the tail. The minimum pressure at the water pipe inlet has been improved. It should be noted that under different calculation models, the layout of the draft tube outlet of the unit to the tail water surge tank is the same, and they are all pressurized flow, therefore, under the same working conditions, the water hammer pressure drop at the
draft tube inlet of different calculation models is basically the same, which is mainly due to the different initial pressures of load rejection under combined working conditions. In addition, due to the partition effect of the tail water surge tank, the pressure shock of the full flow section in Model 3 did not propagate to the draft tube section. Therefore, for a hydropower station with a tail water surge tank, the open and full flow section in the tail water tunnel has a certain effect on the surge of the surge tank and the draft tube inlet pressure under unfavorable combined conditions.

5. The influence of free surface-pressure flow on the lining structure of tailrace tunnel
During the transition process, the water hammer pressure at the full-flow section will have a certain impact on the lining structure of the tailrace tunnel, in combination with the giant power station, the typical working conditions are selected for the study of the open and full flow during the transition process. The calculation results are shown in Table 3 and Figures 5-6.

| Calculation conditions | Maximum internal water pressure (m) | Maximum internal water occurrence location | Minimum internal water pressure (m) | Location of minimum internal water pressure | Remarks |
|------------------------|-----------------------------------|------------------------------------------|-----------------------------------|-------------------------------------------|---------|
| D3                     | 68.86                             | Steep slope capital                      | 48.69                             | Distance exit 369.60m                     | All pressure flow |
| D4                     | 43.25                             | Steep slope capital                      | 13.80                             | Distance exit 369.60m                     | free surface-pressure flow |

From the calculation results, under working condition D4, there was a short-term rapid pressure fluctuation during the free surface-pressure flow alternating, the maximum amplitude of the fluctuation is 16m, but the pressure fluctuation decays faster, and the result is smaller than the extreme result under the pressure flow condition D3. This is mainly due to the effect of the surge chamber that makes the gradient of the water flow change slower, and the full-flow pressure fluctuation range and the fluctuation duration are relatively short. Therefore, the full flow effect of the power station has less influence on the lining section of the tailrace tunnel, even if the alternating flow phenomenon occurs during the later operation of the power station, the pressure will not exceed the design standard of the tunnel lining pressure.

6. The influence of open and full flow on the operation stability of the unit
The electro-hydraulic regulating device has a frequency adjustment function for the unit. When the unit
is running in parallel, when the grid frequency change exceeds its frequency/speed dead zone, according to the inherent ability of the frequency static characteristic (difference characteristic), according to the set rate of adjustment εp/Eternal state Slip coefficient bp Change the unit active power by itself, to ensure the stability of the grid frequency.

The hydraulic turbine adjustment system in the opening adjustment mode and the power adjustment mode can be used in the calculation of a frequency modulation, the former takes the guide vane/needle opening as the response target, and the latter takes the unit's active power as the response target. Calculation formula and method of target power:

$$\Delta P = Pr \times \frac{[(50-Fn) - Ef]}{(ep \times 50)}$$

Among: $\Delta P$ is the unit power increment corresponding to the frequency deviation $\Delta f$ (relative quantity) [MW]; Fn is the grid frequency [Hz]; Ef is Manual frequency for speed control system (Speed) dead zone (Absolute quantity, Hz); ep is the adjustment coefficient of the speed control system; Pr is the unit power (MW).

Compare and calculate the free surface-pressure flow condition TP1 and the pressurized flow condition TP2 respectively, adopt frequency difference-opening adjustment mode. The calculation result of a frequency modulation comparison is shown in Figure 7-8.

From the above calculation, it can be seen that at the initial stage of frequency interference, due to the "separate" effect of the surge chamber, the bright full flow effect will not affect the primary frequency modulation parameters of the unit, The TP1 and TP2 operating conditions of the guide vane opening and the unit output change process line basically coincide at the initial stage of the disturbance. In the late stage of regulation, due to the rapid convergence of the water level fluctuation in the surge tank under the full flow condition, the output of the unit under TP1 condition can quickly enter a stable state.

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**Fig.7 Change process lines of the opening of the guide vane, unit output and the water level of the surge chamber in condition TP1**

**Fig.8 Change process lines of the opening of the guide vane, unit output and the water level of the surge chamber in condition TP2**
7. Conclusion
The setting of the tail water surge tank will not change the free surface-pressure flow pattern of the tailwater tunnel, but after the tail water surge tank is installed, objectively "separate" the sharp pressure fluctuations in the open and full flow section of the tailrace tunnel from being transmitted to the draft tube, improved the operating stability of the unit and the minimum pressure at the draft tube inlet; The maximum pressure in the open and full flow section of the tailrace tunnel is due to the “separate” effect of the surge chamber, the full flow effect of the tailrace tunnel can be relieved to a certain extent, and the structural safety of the tailrace system can be guaranteed; The three flow regimes have little effect on the regulation quality of the unit, and the primary frequency regulation performance can meet the requirements. But in the process of the occurrence of open full flow, although the maximum pressure did not exceed its design standard, However, the fatigue damage caused by pressure pulsation and the effect of local air stagnation in the open and full flow section on concrete erosion should still be paid attention to. This phenomenon should be further studied.

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