Study on measures of preventing and reducing silting of old hydropower stations in high sediment content reservoir area

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Abstract. For water conservancy projects that have been built on rivers with high sediment concentration, the sediment deposition is the primary problem affecting safe operation. Based on a large hydropower station already built on the Yellow River, combined with model test, simulation analysis and other methods, this paper proposes that the effective method to solve the sediment problem is to use the newly built desilting tunnel to arrange the water diversion power generation system, and give the measures to solve the siltation of power generation hole and surge chamber involved in this method. The engineering practice shows that the siltation prevention and reduction measures mentioned in this paper can effectively solve the siltation problem of the old hydropower station in the high sediment content reservoir area.

1. Introduction
According to the results of the first national water conservancy survey, China has 98002 reservoir projects built or under construction, of which nearly 90% were built before the 1980s [1]. Most rivers in China have high sediment concentration and heavy sediment transport, the annual sediment transport capacity of the seven major rivers is 2.3 billion tons, especially some rivers in northwest and north China, the sediment concentration is very high. For example, in Zuli River of Gansu Province, the sediment concentration of rivers in flood season is greater than 1000kg/m³ [2].

For important water conservancy projects that have been built on rivers with high sediment concentration, because of silting, serious hidden dangers have been brought to the safe and economic operation of the reservoir. The conventional situation is to use the existing flood discharge and sand discharge facilities [3], and the effect is obvious when the reservoir runs for a certain period of time. However, with the further increase of silting amount and silting bed surface, the silting pattern is further deteriorated, and the existing flood discharge and sand discharge facilities are difficult to implement large-scale sand discharge or the implementation effect is poor, it is difficult to effectively solve the problem of sediment. The Yellow River is the sediment content is one of the biggest river in the world, in this paper, based on a large hydropower station already built on the Yellow River, combined with model test, simulation analysis and other methods, put forward the effective solution to the sediment problem is to build a new sand drainage tunnel, and in its hole bifurcation diversion...
installed power generation, one hole serves two purposes, not only effectively solve the siltation in front of the reservoir dam, but also increase the power efficiency, which provides an important reference for preventing and reducing silting of old hydropower stations in the high sediment content reservoir area.

2. Relying on the project
Based on the project reservoir area is mainly density current, which is the relative movement of two or more fluids with little difference in specific gravity that can be mixed due to the difference in specific gravity [4]. In general, the sediment concentration of the water forming the density current is high, and the maximum sediment concentration can reach more than 100kg/m³, once the sediment in the density current is silted, it will pose a great threat to the normal operation of sand discharge and power generation.

During the nearly 50 years of operation of the hydropower station reservoir, the whole reservoir has deposited nearly 1.7 billion m³ of sediment, and the reservoir capacity has lost about 30%. Since 1974, in the flood discharge and sand discharge building of the reservoir, more than a hundred times of sediment discharge by density current and four times of sediment discharge by low water level have been carried out, which have played a positive role in alleviating sediment deposition in front of the dam. However, since 1978 dead storage capacity full of silt, the reservoir area is a natural river course, gradually lose the ability of sediment, river sand to reach before the dam in the form of density current, although most of them can be discharged out of the reservoir (about 60%), the siltation in front of the dam is still obvious, to alleviate the effect of sediment deposition was not significant, machine sand wear serious [5]. The existing sand discharge facilities can not completely solve the serious damage caused by siltation in front of the dam to the reservoir. Therefore, how to solve the sediment problem is the key to improve the safety of the reservoir.

3. The solution to the sediment problem
To solve the problem of sediment deposition, specific solutions should be determined according to the conditions of water and sediment, the law of siltation transport in the reservoir area, the present situation of siltation in the reservoir, the main problems or hazards caused by siltation in front of the dam, and the natural conditions such as the topography of the reservoir. Relying on the original sand drainage measures of the project, the main use of the left bank drainage channel, the right bank sand drainage tunnel and other facilities to carry out density current sand drainage, low water level sand pulling and upstream combined regulation, these measures played a certain role in the early and middle period of the reservoir operation, but the reservoir sediment deposition problem is still serious, and have not been effectively resolved. The normal operation of the power station can be ensured only by effectively controlling and reducing the sand deposition elevation, relieving the speed of silting back in front of the dam and reducing the silting over the machine. The way out to solve the problem of reservoir sediment is to solve the problem of how to discharge sand more efficiently and reduce the amount of sediment before reaching the dam. Its essence is how to discharge the sediment before reaching the dam. According to the study, "one hole can be used for two purposes", by adding sand drainage tunnel to divert water to generate electricity, as shown in Figure 1, the silt can be intercepted and discharged into the reservoir near the dam front, which is also an ideal solution.

Figure 1. Floor plan.
The particularity of desilting tunnel to arrange water diversion power generation system is to "borrow" sand drainage tunnel installed, that is, when the storage sediment concentration is large, sand discharge, or clean water power generation. Its advantage is that it can not only lose the opportunity to drain sand, but also can use clean water to generate electricity, so that desilting tunnel is in the "regular running water" state, to ensure desilting tunnel is not silted up, at the same time, it can make use of abandoned water power generation to obtain benefits, improve the capacity of peak regulation and frequency modulation of the system, and extend the maintenance period of the unit, ensure the system safe and stable operation.

The main function of desilting tunnel is to drain the reservoir sediment, and the main purpose of bifurcation water diversion power generation in the desilting tunnel is to prevent silting in the non-sand drainage period. Therefore, the core problem is that the water flow through each part of the water diversion power generation system has a large sediment concentration, the flow with high sediment content will produce siltation in the building or cause wear and cavitation damage on the flow surface, which will bring great risks and safety hidden dangers to the normal operation of the project. So, it is important to solve power generation tunnel blockage and surge chamber siltation problems, when desilting tunnel to arrange water diversion power generation system.

(1) The blockage problem of power generation hole

Using a constant water and sediment process, the desilting tunnel runs alone, the sand concentration in the desilting tunnel is 100 kg/ m³, in the first day of the sand-discharging operation, the amount of sediment in the power generation hole can reach about 70% of the total amount of sediment, the maximum deposition thickness of sediment is basically 5 m~6 m, the next day is 7 m~8 m, and the third day reaches more than 9 m. Figure 2 shows the sediment deposition pattern in the power generation hole after 1 day of sand drainage.

(2) The siltation problem of surge chamber

Under the working condition of water diversion power generation system, the sediment concentration of water flow is 20 kg/m³ ~ 40 kg/ m³, sediment test results show that if there is no special silting reduction treatment inside the surge chamber, the silting at the bottom of surge chamber is serious, as shown in Table 1, Figure 3 shows the sediment deposition pattern of the surge chamber after 15 days of power generation. The maximum thickness of floor deposition occurs near the side wall of surge chamber. The larger the flow of the power generation hole is, the more violent the flow turbulence of the water flowing into the surge chamber through the impedance pipe is, the stronger the sediment carrying capacity of the upward flow is, the higher the deposition velocity of the floor of the surge chamber is, and the higher the deposition thickness is.

Table 1. Maximum sediment deposition thickness and deposition velocity of surge chamber floor under power generation condition.

| Power generation time | Deposition thickness (m) | Deposition velocity (m/d) |
|-----------------------|-------------------------|---------------------------|
|                       | 5 Days                  | 10 Days                   | 15 Days                   |
| Single unit generation| 3.8                     | 0.76                      | 5.9                       | 0.59                      | 8.08                     | 0.54                      |
| Two units power generation| 6.12                  | 1.22                      | 9.44                      | 0.94                      | 9.56                     | 0.64                      |
Figure 2. Sediment deposition pattern of power generation hole after desilting tunnel working 1 day.

Figure 3. Sediment deposition pattern of surge chamber after power generation hole working 15 days (Two units power generation).

4. Measures to prevent and reduce silt

4.1. Power generation hole silt prevention

The desilting tunnel has high pressure, high flow rate, and the bifurcation shape of the power generation hole is relatively complex. Therefore, the key to the layout of the water diversion power generation system by using the desilting tunnel is how to arrange the appropriate power generation hole, that is, the selection of the bifurcation angle of the power generation hole and the flow pattern at the bifurcation are one of the key points. Relying on the project, the power generation hole is connected to the end of the bifurcation section of the desilting tunnel, which is a pressure tunnel. The length of the power generation hole is 261 m, and the inner diameter of the tunnel is 10 m. The overcurrent flow rate of the power generation tunnel is 366.5 m³/s, and the maximum flow rate in the tunnel is 4.6 m/s. Combined with the engineering characteristics, 30° and 40° were selected to carry out the comparison research of clear water test and muddy water test.

In terms of velocity distribution, time mean pressure, pulsation pressure and pressure slope along the path in clear water test, there is little difference in the hydraulic characteristics between the two bifurcation angles. However, from the perspective of sediment deposition distribution and amount in muddy water test, 40° is obviously better than 30°. For the single power generation condition, the sediment deposition patterns in the two kinds of bifurcation Angle drainage tunnels are completely similar. For single sand flushing conditions, the maximum thickness of deposition in the position of the obvious difference, as shown in Figure 4, Figure 5, 30° from bifurcation point distance of about 65 m above, and 40° from about 55 m, 40° distance is less than 30° shows that the strength of the return of the former than the latter, the results show that the amount of sediment deposited at a bifurcation Angle of 30° is obviously larger than that of 40°. In addition, under the power generation condition, the sediment volume of the desilting tunnel for 10 days at 30° is 60% larger than that at 40°. Under the condition of sand discharge, the sediment volume of power generation tunnel in 3 days at 30° is 16% larger than that at 40°.

Figure 4. Sediment deposition process of power generation tunnel under the condition of 30° bifurcation Angle.

Figure 5. Sediment deposition process of power generation tunnel under the condition of 40° bifurcation Angle.
4.2. Silt reduction technology in surge chamber

After research, the shape of the floor of the surge chamber adopts the "funnel-shaped" design, and the connection mode between the impedance hole bottom and the upstream gradient section at the bottom of the surge chamber is adjusted from the traditional linear or circular connection mode to the "inverted L-shaped" broken line type. Figure 5 and 6 are the shapes of conventional and new type surge chambers. For flow areas with high sediment content, if the traditional horizontal design is used in the surge chamber floor, the flow velocity of the impedance orifice is large, and the water rising from the impedance orifice to the surge chamber diffuses to all sides, after the water diffused to the upper part of the surge chamber, the flow turbulence intensity was obviously weakened, causing the impedance to rise and the large amount of sediment carried into the surge chamber to deposit on the surge chamber floor, especially for impedance surge chambers with large stable cross-section and high wellbore, the bottom plate cleaning work is more difficult. The long-term floor deposition is not conducive to the function of surge chamber, and will cause the water level in the surge chamber to rise even beyond the height of the designed large well, causing serious harm.

Mathematical model is used to simulate the operation conditions of two power plants, and the traditional structure and the new structure of the surge chamber are compared and studied. Table 2 shows the comparison of flow velocity at the top of the impedance orifice and flow turbulence intensity in the surge chamber. The height difference between upstream tunnel top and downstream tunnel top at the bottom of the surge chamber is 4m, if the surge chamber floor is horizontal, the formed parapet blocks a larger part of the upstream inflow into the impedance hole of the surge chamber, the flow velocity through the impedance hole of the surge chamber is larger, up to about 3.2 m/s; the flow turbulence height in the surge chamber is larger, up to about 26.2 m; the longitudinal profile of the flow turbulence in the surge chamber is wider, up to about 3.3 m, the flow turbulence in the surge chamber is large, and the flow rising through the impedance hole can carry more sediment. However, the new structure obviously reduces the flow turbulence intensity on the impedance of the surge chamber and the flow turbulence intensity in the surge chamber.

| Project       | Top of impedance orifice flow velocity (m/s) | Height of flow turbulence in the surge chamber (m) | Width of flow turbulence in the surge chamber (m) |
|---------------|---------------------------------------------|---------------------------------------------------|-----------------------------------------------|

Figure 6. Conventional structure of surge chamber.  
Figure 7. New structure of surge chamber.
In addition, the sediment test shows that the maximum siltation thickness after reaching equilibrium in the new structure of the surge chamber is about 6 m, which is about 3.6 m less than the conventional structure (9.56 m), which is about 36% less. The equilibrated silt volume in the surge chamber is about 1230 m³, a 48% reduction compared to the conventional structure (2360 m³). By adopting the new structure, the silt in the surge chamber can be discharged smoothly, and the "funnel cyclone" can be used to effectively reduce the siltation range and thickness of the floor. Figure 8 shows the comparison of siltation thickness of the surge chamber.

![Figure 8](image)

**Figure 8.** The relationship between siltation thickness of surge chamber and power generation time.

### 5. Conclusion

The project of this paper uses the newly-built desilting tunnel to arrange 2 generating units. After the project was completed and put into operation in 2018, the sand discharging effect is good. The sand discharge ratio increased from 60% to 95.3%, and the sediment concentration of the original unit was obviously reduced from 11.9 kg/m³ to 3.93 kg/m³. The practice shows that the sedimentation in front of the dam can be effectively solved, the sediment concentration of the reservoir can be reduced, and the original function of the reservoir can be restored or improved by adding the desilting tunnel to divert water to generate electricity and adopting certain technology of preventing and reducing silt.

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