Analysis of bulge mechanism of penstock of a hydropower station

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Abstract. In this study, the deformation and leakage of pressure steel pipe in a hydropower station were investigated and analyzed. Through calculation and theoretical analysis, it is concluded that due to the failure of the external drainage system, when the internal water extravasation, the external water pressure can not be eliminated in time, resulting in excessive water pressure and deformation of the external steel pipe. As a thin-shell structure, the pressure steel pipe is prone to buckling and instability when subjected to external pressure, and bulging or pipe wall compression often occurs. Stability against external pressure has become an important factor affecting the safety and stability of pressure steel pipes. Therefore, even under normal working conditions, steel pipe without the stiffening ring can meet the external pressure stability, and the design can also consider setting the stiffening ring, because the stiffening ring has a strong ability to resist external pressure.

Keywords: hydropower station; penstock; bulge mechanism

1 INTRODUCTION

The pressure steel pipe can be divided into open pipe and buried pipe, which is buried in rock mass or concrete. The pressure steel pipe mainly bears the internal water pressure during the normal operation of the power station, and the concrete and surrounding rock can jointly bear the pressure steel pipe [1-2], even the surrounding rock can bear all the internal water pressure [3-4], and the damage caused by the internal water pressure of the pressure steel pipe is very rare. As a thin-shell structure [5-6], the pressure steel pipe is prone to buckling and instability when subjected to external pressure, and bulging or pipe wall compression often occurs. Stability against external pressure has become an important factor affecting the safety and stability of pressure steel pipes [7].

The significance of studying deformation leakage of pressure steel pipe can be analyzed from two aspects: scientific research and engineering practice. Firstly, by deeply studying the mechanism and influencing factors of deformation and leakage of pressure steel pipes, we can better understand the behavior and characteristics of these thin shell structures. This is of great significance for the development of basic theories in the

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fields of material mechanics, structural mechanics and geotechnical engineering. In addition, the study of pressure steel pipe deformation leakage is helpful to reveal the failure mechanism of pressure vessel, which is of great significance to improve the safety and reliability of engineering structures.

From the perspective of engineering significance, the safety and stability of pressure steel pipe, as a key structure used for conveying fluids, is directly related to the normal operation of engineering systems and personal safety. When the pressure steel pipe deformation leakage, in addition to may lead to the system pressure out of control, but also may cause environmental pollution, economic losses and even casualties and other serious consequences. Therefore, it is of great value for engineering design, construction and maintenance to deeply study the mechanism and prediction method of deformation and leakage of pressure steel pipe.

In addition, the reason why it is worth studying the deformation and leakage of pressure steel pipes, there are the following reasons. First of all, with the continuous growth of energy demand, the use of pressure steel pipes is expanding. Understanding the mechanism and characteristics of deformation leakage can provide scientific basis for more extensive engineering applications. Secondly, although the surrounding rock and concrete can bear the pressure of the pressure steel pipe to a certain extent, in actual engineering, the deformation and instability of the pressure steel pipe itself is still a potential safety hazard. Therefore, it is necessary to further study the pressure stability of the pressure steel pipe to improve the safety of the engineering structure. Finally, with the development of science and technology, it has become possible to use advanced modeling and simulation technology to predict the deformation and instability behavior of pressure steel pipes, which provides a new opportunity for further research on the deformation and leakage of pressure steel pipes.

Therefore, the research significance and engineering significance of in-depth study of pressure steel pipe deformation leakage is to improve the understanding of its behavior and characteristics, as well as improve the safety and reliability of engineering structures. It is of great significance to ensure the normal operation of engineering system, the life safety of personnel and the protection of environment.

The past research mainly focused on the analysis and experimental research of the internal pressure, external environment and the properties of the material itself. These studies provide us with a basic understanding of the deformation leakage of pressure steel pipes, using a wealth of models and theories, as well as a large number of experimental data.

However, in terms of insufficient research, there are still some problems that need to be further solved. First of all, previous studies mainly focused on theoretical models and experimental analysis, lack of in-depth observation and record of the deformation and leakage behavior of pressure steel pipes in practical engineering. Therefore, we still lack a comprehensive understanding of the actual deformation and leakage of pressure steel pipes under different engineering environments. Secondly, the existing research on the prediction and monitoring methods of deformation leakage of pressure steel pipes is still limited, especially the comprehensive research on deformation leakage mechanism under different stress states, environmental conditions and material characteristics is still weak. In addition, the research on the coupling effect of pressure steel pipe with surrounding rock, concrete and other external environment is still not deep enough, which has important application significance in practical engineering.

In summary, although the past research has provided us with a basic understanding of the deformation and leakage behavior of pressure steel pipes, it is still necessary to further study the deformation and leakage mechanism, prediction method and monitoring technology of pressure steel pipes to meet the needs of engineering practice for safe, reliable and efficient conveying systems. Therefore, the research on deformation leakage of pressure steel pipe still has important scientific value and engineering significance.

2 DESCRIPTION OF ISSUES

A hydropower station is a concrete-faced rockfill dam consisting of four 150MW Francis turbine generating units and a switch station. The power station has been in operation since 1990.

In 2020, the owner found that the steel lining of the penstock near the lower bend bulged into the pipe, as shown in figure 1, and the bulging area accounted for about 80% of the cross-sectional area of the penstock, as shown in figure 2.

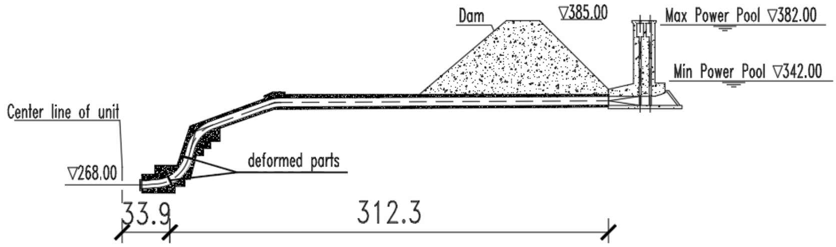

Fig. 1. Schematic diagram of the bulge site

Fig. 2. Steel-lining bulge photos in 2020

In late July 2023, the owner found serious leakage at the original deformation of the penstock and then emptied the penstock. According to the inspection situation, the following problems were mainly found:

The inward bulging deformation of steel lining has decreased compared to 2020, and the deformation area has been reduced from about 80% in 2020 to about 25%, as shown in figure 3. There are two tear points in the middle of the adjacent pipe section on the right side of the steel lining deformation position (lower left), which are named TP1 (upstream) and TP2 (downstream) in sequence according to the upstream and downstream directions, as shown in figure 3. It was found at the site that there were two obvious water leakage in the penstock, one leaked from the upstream of the penstock with a larger water flow, and the other leaked from the tear point TP2 of the steel lining with a smaller water flow, as shown in figure 3. Right above the penstock deformation and bulging position, the water flow of the discharge has obvious jumps, so it can be judged that there is an obvious stagger phenomenon along the circumferential pipe joint, as shown in figure 4.

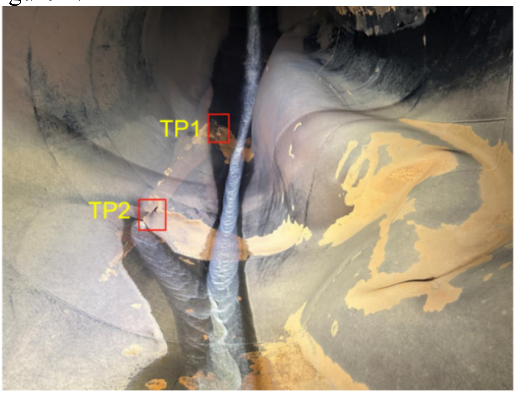

Fig. 3. Deformation and tear point location at the lower end of the penstock

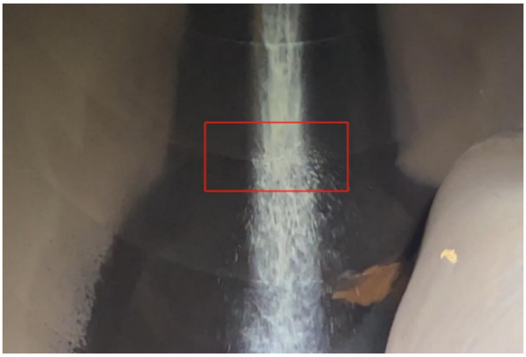

Fig. 4. The staggering of the steel lining weld along the descending pipe section

There are obvious leakage points at the upper and middle parts of the inclined penstock section of penstock buried concrete, which is accompanied by the development of cracks. At present, penstock is empty, and there is still a small flow of water leaking out from the cracks. There are two water leakage points in the inclined penstock section, named CP1 and CP2 respectively, as shown in Figure 5.

Fig. 5. Water leakage points on the outer concrete at the inclined pipe section of penstock

3 RECOMPUTATION

The steel plate material adopt high strength steel Q345R with thickness of 22mm, and yield strength σs of 325Mpa, tensile strength σb of 500Mpa, strength design value f of 290Mpa.

The internal water pressure of the pressure steel pipe is calculated according to the appreciation of 30% pressure, and the steel pipe bears all the pressure, and the outsourcing concrete is considered as a safety margin.

According to the "pressure steel pipe design Code for Hydropower Station" (NB/T 35056-2015), the stress of each calculation point of the steel plate should not be greater than its resistance limit:

$$\sigma_R = \frac{1}{\gamma_0 \varphi \gamma_d} f \tag{1}$$

Where: σ_R – Resistance limit(N/mm2);

γ_d – Structural coefficient, 1.25 for buried pipe;

φ – Design condition coefficient, according to the specification, the durable condition φ is 1.0;

γ_0 – Structural importance coefficient, this project belongs to the I grade project, the high pressure pipeline belongs to the corresponding level 1 building, the steel pipe structure safety level is level 1, then γ_0 is 1.1.

The steel pipe resistance limit value σ_R is 210.9Mpa. The steel pipe structure design is as follows:

1) Structural calculation of internal pressure resistance (End of inclined shaft EL.287.00m)

The radius is 3615mm, the thickness of the steel pipe is 22mm (including 2mm corrosion thickness), the internal water pressure is 1.227Mpa(0.932Mpa hydrostatic pressure plus 0.295Mpa water hammer pressure).

$$t = \frac{\Pr}{\sigma_R} = \frac{1.227 \times 3165}{210.9} = 18.16\text{mm} < 20\text{mm} \tag{2}$$

The internal pressure stability of the steel pipe can meet the requirements.

2) Structural calculation of external pressure resistance (End of inclined shaft EL.287.00m)

When the internal water extravasates, the external water pressure is equal to the internal water pressure equal to the total water head.The external water pressure is 0.932Mpa(9.81*(383-287)*0.001).

$$P_{cr} = 612(\frac{t}{r})^{1.7}\sigma_s{}^{0.25} = 612(\frac{20}{3165})^{1.7}325^{0.25} = 0.47\text{M}pa < 0.93Mpa \tag{3}$$

When the internal water is leaking out, steel pipe without the stiffening ring can not meet the external pressure stability, and it is necessary to set a stiffening ring to ensure the stability of the tube wall.

4 ANALYSIS OF CAUSES

The main reason for the instability of the lower bending section of the penstock is the internal water leakage during the operation period, and during the venting process, the excessive external water pressure resulted in the instability of the steel pipe. The inspection found that the penstock had dislocations along the weld, and was also presenting some cracks. In the process of emptying the penstock, the external water pressure cannot be discharged in time due to the failure of the external drainage of the steel pipe, which causes the outer part of the steel pipe to bear excessive external water pressure, resulting in inward deformation. After 2020, during the continuous operation for 3 years, the local weak point of the steel lining was torn under the action of external water pressure. After the tear occurred, on the one hand, the infiltration of internal water intensified and the leakage became more serious and seriously threatening to the safety of the penstock. On the other hand, when the penstock is empty, these torn parts can quickly release the external water pressure, so that the inward deformation of the steel pipe is alleviated, and there is a like recovery under the internal water pressure.

In addition, from the current water leakage situation at the tear point TP2 found during the inspection, the external water in the lower end of the penstock could also come from groundwater or leakage water from a nearby structure, but due to the very low pressure and very small water volume, this could not the main factor for the external pressure instability of penstock.

In addition, it is very unlikely that the water in the lower end of penstock comes from the upstream reservoir because the upstream reservoir is far away from the lower horizontal section. If it comes from the upstream reservoir, it will already appear at the leakage point of the downward inclined slope. Therefore, it is not considered that the instability of the steel pipe in the lower horizontal section has much to do with the seepage of the upstream reservoir.

5 CONCLUSION

Through this study, the future engineering construction pressure steel pipe design can learn from the experience, especially the need to pay attention to the damage that may be caused by external water pressure. As a cheap and efficient engineering measure to prevent external pressure damage, stiffening ring should be paid more attention and applied in design and construction. In this study, the causes of deformation and leakage of pressure steel pipe in a hydropower station are investigated and analyzed. It is found that internal leakage and drainage system failure lead to excessive water pressure outside the steel pipe, which leads to the deformation of the steel pipe. After three years of continuous operation, the local weak spot of the steel lining broke, further aggravating the leakage situation. Therefore, even under normal conditions, the steel pipe without the stiffening ring can meet the external pressure stability, but the design should still consider setting the stiffening ring, because the stiffening ring has a strong ability to resist external pressure. This finding has important guiding significance for the design and engineering practice of pressure steel pipe in the future.

This discovery will prompt engineers to pay more attention to the reliability of the drainage system to avoid the adverse effect of external water pressure on the pressure steel pipe structure. In addition, when considering the external pressure stability of the pressure steel pipe, the designer should consider a variety of factors, and if possible, consider the use of engineering measures such as stiffening rings to improve the safety and stability of the structure.

In addition, this study also revealed the existence of weak points in the steel lining and the fracture condition after long-term operation. Therefore, in the future construction of the project, for the material and structural design of the pressure steel pipe, more attention should be paid to the quality of the material and the processing technology, as well as the real-time monitoring and detection of the internal condition of the pressure steel pipe during operation.

All in all, this study provides valuable experience and lessons for the design and use of pressure steel pipes in future engineering construction. Engineering designers can deeply understand the importance of drainage system and material quality for the safety and stability of pressure steel pipes, and take corresponding engineering measures to improve the safety and stability of the structure. At the same time, this also reminds engineering practitioners to strengthen the monitoring and management of possible problems in the long-term operation of pressure steel pipes to ensure the safe and reliable operation of engineering systems.

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