Operation Safety Analysis of Diversion Tunnel with Unfavourable Geology Condition Based on Finite Element Simulation

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Abstract. The diversion tunnel of a hydropower station has unfavourable geological tunnel sections, and many collapses occurred during the excavation construction. It was put into operation after treatment with reinforced concrete lining. However, the operating conditions are quite different from the design conditions: the tunnel is in a low water-level operation or emptying state for a long time. Therefore, a safety analysis of the tunnel section is required. In this paper, a 3-dimensional finite element model is established by reasonable geological parameters for numerical simulation. The simulation results show that the support lining scheme during construction can temporarily guarantee the stability of the surrounding rock and the safety of the lining structure. However, the reducing strength security reserve coefficient of the surrounding rock is relatively low. It is recommended to strengthen monitoring and regularly inspecting of tunnel emptying.

1. Introduction
A hydropower station consists of diversion structures, ground workshop and substation. Water diversion system structures include diversion canals, intake, diversion tunnel, surge shaft and penstock. Among them, the length of the diversion tunnel is 1498m, which is a 10.2m × 10.4m horseshoe section. According to the design scheme for normal operation of the reservoir, the bottom elevation of the intake is 80m, the upper edge elevation is 89.3m, the minimum diversion elevation is 95.0m, and no electricity is generated when the reservoir water level is lower than 90m. However, after the hydropower station was put into operation, it is blocked or shut down about 75% of the time, and the time of the complete shutdown is close to 30%. This is due to the fact that the reservoir maintains a low-water level for a long time and frequently runs below the dead water level of 95m, and the hydropower station has insufficient time to deliver its rated capacity.

The diversion tunnel with unfavorable geological sections, is in a low water-level operation or emptying state for a long time. Therefore the long-term safety of the tunnel operation needs to be calculated and analyzed. In this paper, through the verification of geological data and on-site investigation, the most dangerous unfavorable geological tunnel section of the diversion tunnel is determined, and its operational safety is analyzed through three-dimensional finite element calculation, so as to provide a reference for the long-term operational safety of the project.
2. Calculation Data

2.1. General Situation of Unfavorable Geological Section
The diversion tunnel with a stake number of 0+785m ~ 0+830m is mainly gneiss. The section contains schist-developed fault zones. The faults and joints constitute an unstable combination and the rockmass is of poor quality. During the excavation process, multiple collapses occurred in this section of the tunnel, and the deformation of the tunnel failed to converge after the treatment with shotcrete anchoring. Finally, 1.0m thick reinforced concrete lining was used for support, and the backfill grouting was applied to the collapsed area. The multiple emptying inspections during the operation period has shown that the operation of the tunnel is in good condition, and no abnormal phenomena such as cracks and water seepage have been found on the surface of the lining concrete.

2.2. Calculation Parameters
The surrounding rock classification of the tunnel section with unfavorable geology condition is Type V, the thickness of the overlying strata is 150m, the groundwater level is 122m above the top of the cave, and the excavation section is a horseshoe section of 10.2m x 10.4m. After excavation, spray anchor support is used as a temporary support measure. The bolt parameters are φ19mm@1.2m×1.2m, the length is 3.0m, and the thickness of the sprayed concrete layer is 10cm. The reinforced concrete lining with a thickness of 1.0m is used as the secondary support.

The deformation modulus of surrounding rock is 1.5 GPa, Poisson’s ratio is 0.35, rock mass friction coefficient is 0.45, cohesion is 0.2 MPa. The grade of lining concrete is R200, elastic modulus is 25.5 GPa, compressive strength standard value is 13.4 Mpa, tensile strength standard value is 1.54MPa. The anchor steel bar has an elastic modulus of 200GPa and a design strength of 300MPa.

2.3. Three-dimensional finite element calculation model
The finite element grid of diversion tunnel rock is divided by 8-node hexahedral elements, the total number of elements is 51740; the lining concrete is divided by 8-node hexahedral elements, and the number of elements is 984; the concrete spray layer is divided by 4-node shell elements. The number is 624; the anchor rod is simulated by a 2-node rod element, and the number of elements is 2520. Figure 1 is the three-dimensional finite element calculation model of the diversion tunnel, and Figure 2 is the initial in-situ stress distribution before excavation.

![Figure 1. Finite element model of headrace tunnel](image-url)
3. Diversion tunnel safety calculation and analysis

3.1. Calculation and analysis of excavation support

The calculation idea of the numerical simulation of tunnel excavation is that the elastic release load of the surrounding rock is borne solely by the surrounding rock, and support measures are applied immediately after the excavation is completed, and the plastic adjustment load and seepage load increment are jointly borne by the surrounding rock and the support measures [1, 2]. In this calculation, the tunnel excavation is simulated first, and the temporary shotcrete anchor support measures are applied immediately after the excavation is completed. After trial calculation, it is found that the finite element calculation cannot be converged under the action of plastic adjustment load, which means, the surrounding rock cannot maintain self-stability under temporary support measures [3], and the calculation result is consistent with the situation that the surrounding rock cannot be self-stabilized in actual construction.

According to the actual construction situation, when the surrounding rock reaching critical stability, the further simulated is using 1.0m thick reinforced concrete lining to secondary support on the surrounding rock, and the lining, shotcrete support and surrounding rock jointly undertake the released load in excavation and the incremental seepage load.

As the permeability coefficient of the lining concrete is much smaller than that of the surrounding rock, the local seepage field of the unfavorable geological tunnel section changes after the lining. The seepage pressure distribution of the surrounding rock and lining when the seepage is stable is shown in Fig. 1.

![Figure 2. Crustal stress (Unit: Pa)](image)

The calculation result shows that the finite element calculation can be converged after the lining construction, with the plastic adjustment load and incremental seepage load, which means, the surrounding rock can maintain stability after the lining is applied. The deformation, stress, yield and distribution of the lining stress when the surrounding rock reaches a stable state after the lining are shown in Fig. 4 to Fig. 7.
From the calculation results, as far as the surrounding rock deformation is concerned, after the tunnel surrounding rock is stabilized, the maximum deformation of the surrounding rock is about 6.89 cm, and...
the maximum deformation occurs in the middle of the side wall. As far as the surrounding rock stress is concerned, after the tunnel surrounding rock is stabilized, the maximum tensile stress is about 0.55 MPa, which appears on the surface of the middle of the side wall; except for the area where the bottom corner stress is concentrated, the maximum compressive stress of the surrounding rock is about 11.6 MPa, which appears in the deep part of the side wall, about 7.0m away from the side wall surface. As far as the yield of surrounding rock is concerned, after the tunnel is stabilized, there are yield zones in the top arch, side wall, and bottom plate. Among them, the yield zone outside the side wall is larger, and the yield degree is more serious. The maximum yield zone near the intersection of the side wall and the top arch reaches about 7.4m. As far as the stress of concrete lining is concerned, due to the large deformation of the rock mass at the location of the side wall, the lining side wall plays a good role in supporting the surrounding rock, which greatly limits the deformation of the surrounding rock in the area of the tunnel side wall. Bending deformation occurs under the action of rock pressure, so tensile stress appears on the inner side of the middle and upper part of the side wall, but the magnitude is not large, about 0.4MPa; the compressive stress of the lining is small, the maximum value is about 6.0MPa, which appears on the inner side of the bottom of the side wall. In addition, due to the assumption that the surrounding rock and the lining are well bonded in the calculation and simulation, a large-scale tensile stress zone appears outside the bottom of the side wall. In actual situations, there may be a shift between the surrounding rock and the lining in this area. Such a large tensile stress will not be generated.

For the underground tunnel project, the long-term external water pressure without internal water is the most dangerous working condition, and the long-term low water level operation of the diversion tunnel has a low water pressure, and the complete emptying is used as the diversion tunnel safety calculation condition is partial to security. Therefore, from the above calculation results, it can be seen that under the existing support measures, the finite element calculation of the poor geological tunnel section of the diversion tunnel can converge under the low water level operating state. Although the surrounding rock deformation and yield range are large, due to the support of the lining Effect, the surrounding rock of the tunnel can maintain stability. It can be seen from the bending stress distribution of the lining side wall that the lining structure is also safe because the lining tensile stress is small.

3.2. Analysis of Stable and Safe Reserve of Surrounding Rock

Although the poor geological tunnel section of the diversion tunnel can be maintained temporarily, its long-term operation safety deserves attention. Therefore, the strength reduction safety reserve factor of the surrounding rock of the tunnel is further analyzed by the finite element strength reduction method [4-6], that is, on the basis of the calculation of the stability of the surrounding rock deformation, the strength parameters of the surrounding rock are continuously reduced in proportion to obtain the Fig. 8. For the relationship between the characteristic point displacement and the strength reduction factor, Fig. 9 shows the lining stress distribution when the strength reduction factor reaches 1.07.

In the calculation of the finite element strength reduction method, the non-convergence of the calculation, the penetration of the plastic zone of the surrounding rock and the sudden change of the displacement of the characteristic point are used to determine the safety factor of the stability of the surrounding rock [3]. In this calculation, the abrupt displacement of characteristic points combined with lining stability (stress) is used as the criterion of surrounding rock stability. From the calculation results, it can be seen that the displacement of the characteristic point in the middle of the side wall of the tunnel increases with the increase of the strength reduction factor, but due to the supporting effect of the side wall, the displacement of the surrounding rock displacement is small. When the strength reduction factor reaches about 1.08, The displacement of the characteristic point in the middle of the side wall increases sharply and suddenly changes. At the same time, from the perspective of the stress of the concrete lining, when the strength reduction factor reaches 1.07, the inner stress of the upper middle of the lining has reached the standard value of the tensile strength of the concrete. If the surrounding rock pressure continues to increase, the lining may be damaged due to bending. Therefore, under the support of the existing concrete lining, the safety reserve factor of the drop strength is about 1.06, and the safety reserve of the surrounding rock of the tunnel is small.
4. Conclusion

The main results and conclusions are as follows:

(1) Poor geological section of the diversion tunnel has poor surrounding rock quality and collapse during construction. The calculation shows that the surrounding rock cannot be self-stabilized after temporary excavation anchor support; the reinforced concrete lining with a thickness of 1.0m is used as secondary support, then the surrounding rock can maintain stability under the water-free working condition (extreme case of low water level operation) and the lining structure is safe.

(2) The calculation of finite element strength reduction method shows that the stable safety reserve factor of the surrounding rock of the poor geological tunnel section under low water level operation is only 1.06, so the safety of this tunnel section under long-term low water level operation can temporarily be guaranteed, but the safety margin is small.

(3) In view of the small safety margin of the poor geological section of the diversion tunnel, it is advisable to periodically evaluate the safety of the diversion tunnel based on the site inspection to ensure the safe operation of the tunnel. At the same time, if conditions permit, it is recommended to install monitoring instruments to monitor the working behavior of surrounding rock and lining.

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