Study on Cavity Stress and Deformation after Grouting to Fill Up the Lining of Existing Hydraulic Tunnels

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Abstract: Hollow hole after lining of hydraulic tunnel is one of the common diseases in water diversion tunnel engineering. Aiming at the stress and deformation of the post-lining cavity of existing hydraulic tunnels after grouting, a method for assessing the stress and deformation of the post-lining cavity of existing hydraulic tunnels after grouting is proposed by taking a specific case of a section of a water diversion tunnel in Shaanxi Province as a concrete example, which aims to accurately assess the influence of grouting on the stress distribution and deformation of the post-lining cavity of tunnels after grouting. Two working conditions are adopted, working condition I and working condition II correspond to 70% and 50% of the total load of surrounding rock + primary support + steel arch sharing, and 30% and 50% of the total load of lining sharing, respectively. ABAQUS general finite element software was used to carry out detailed analysis and research. The results show that after grouting reinforcement, the main tensile stress of Case I lining is 0.4564MPa, and the safety margin is 64% higher than that before grouting. The main tensile stress of the lining in Case 2 is 0.9152MPa, and the safety margin is increased by 27.9% compared with that before grouting, and the results of the two cases meet the requirements of C25 concrete limit. The research results can not only provide solid theoretical support for the tunnel reinforcement project, but also have significant practical significance in engineering.

Keywords: Existing Hydraulic Diversion Tunnel; Hollow; Grouting Reinforcement; Stress

1. Introduction

During the construction process of tunnel excavation and lining casting, due to the influence of construction templates and other factors, the phenomenon of voids often occurs behind the tunnel [1-2], which not only affects the structural stability of the tunnel, but also may lead to the formation of plastic zone [3-4] around the tunnel. In order to ensure the safety of construction and the long-term reliability of the project, the use of numerical simulation methods to analyze the impact of cavities on tunnel lining [5-6] has become an important research tool.

In view of the various disease problems that may occur in hydraulic tunnels, in recent years, in terms of the assessment of the reinforcement effect, some scholars have used the finite element analysis method to carry out simulation studies on the effect of grouting reinforcement of existing water transfer tunnels, and to explore the change rule of the concrete stress in the cave wall before and after reinforcement [7-11]. Under specific geological conditions, such as water-rich fine sand strata, the grouting reinforcement program requires special consideration [12]. Some studies have shown that the stability and safety of tunnels can be effectively improved by a reasonable grouting reinforcement scheme for this type of strata [13]. In addition, rotary spray grouting technology, as an advanced tunnel reinforcement technology, has also been widely used in actual projects.

At present, for emergencies such as tunnel collapse, the grouting reinforcement and support technology also shows its unique advantages [14-15]. With the progress of science and technology and the deepening of engineering practice, the tunnel reinforcement technology is also constantly developing and improving. From the selection of grouting materials to the optimization of the grouting process to the evaluation of the reinforcement effect, it is necessary to take into account the specific engineering conditions and geological conditions to ensure the safety and stability of the tunnel. However, there are fewer studies on the effects of the before and after laws of grouting densification in the voids behind the existing tunnels.

Aiming at the stress and deformation of the cavity behind the lining of grouting-filled existing hydraulic tunnels, a method for assessing the stress and deformation of the cavity behind the lining of grouting-filled existing hydraulic tunnels is proposed by taking a specific case of a section of a water conveyance tunnel in Shaanxi Province as a concrete example, with the aim of accurately assessing the influence of grouting-filling on the stress distribution and deformation behavior of the cavity behind the lining of the tunnel, and then proposing an effective solution. Through this study, it can not only provide solid theoretical support for the tunnel reinforcement project, but also provide valuable reference for the design and optimization of the reinforcement scheme in the actual project. These results not only have a high academic value, but also have significant practical significance in engineering.

2. Modeling

2.1 Calculation Conditions

The cross section of the tunnel is 3.6m×3.04m (width×height), the straight wall is 3.2m high, and the top arch is 180°. The initial lining thickness is 12cm, lining thickness is 40cm, steel arch size is 0.118×0.1. 25mm diameter, 2.0m length, 1.0m spacing between rows of anchor rods are used, Φ8 reinforcement mesh is hung in the side wall of the top arch (150mm × 150mm), and C20 concrete is sprayed 120mm thick, in the shape of plum blossom arrangement. The top arch is backfilled with grout within 100°, and the grouting pressure is 0.2MPa. The thickness of the equivalent compression zone formed by the anchor rods is:

$$b = L - \frac{2R\tan\left|\frac{D}{2R}\right|}{\left(1-\tan\frac{D}{2R}\right)\left(\cos\frac{D}{2R}+\sin\frac{D}{2R}\right)} = 0.54m \quad (1)$$

Where D is the anchor spacing in the reinforcement measure;

L is the anchoring depth of anchor rods in the reinforcement measures;

R is the equivalent radius, according to the 1.0m spacing arrangement of portal anchors, fixed anchors along the whole section of the tunnel uniformly arranged, the average spacing is 1.0 m. Its equivalent radius is $R = \sqrt{\frac{S}{\pi}}$, S is the area of the tunnel, the value is: $S = \frac{180°}{360°} \times \pi \times r^2 + B \times H$.

Two calculation conditions are set up:

Case 1: Enclosing rock + primary support + steel arch share 70% of the total load of the enclosing rock, and lining share 30% of the total load of the enclosing rock.

Case 2: Enclosing rock + primary support + steel arch share 50% of the total load of the enclosing rock, lining share 50% of the total load of the enclosing rock.

The stress and deformation patterns of existing hydraulic tunnel lined cavities were analyzed before and after grouting for the two conditions respectively.

2.2 Calculation Model

In order to accurately analyze the stress and deformation of the lined cavities of existing hydraulic tunnels before and after grouting. The concrete structure of the primary lining and the second lining adopts the concrete damage plasticity model proposed by Lubliner, Lee and Fenves. The steel arch is modeled by elasticity model and the surrounding rock is modeled by Mohr-coulomb model. The original design dimensions of the tunnel components in the surrounding rock are taken and the equivalent compression zone is closed. The maximum depth of the hollow and uncompacted parts of the surrounding rock is 321 m. The pressure of the upper part of the tunnel is approximated to be 8.2176 MPa. The top part of the tunnel is modeled as 4 times the diameter of the tunnel, and the lateral and lower parts of the tunnel are modeled as 3 times the diameter of the tunnel.

Since the tunnel does not change much along the tunnel axis, it is a plane strain problem, so the rock body of unit length along the tunnel axis direction is taken as the research object, so as to establish a three-dimensional model for stress-strain analysis, and the size of the model is 45m × 50m × 1m. The calculation model consists of the peripheral rock+primary support+lining+steel arch+equivalent compression zone model, as shown in Figure 1 and Figure 2.

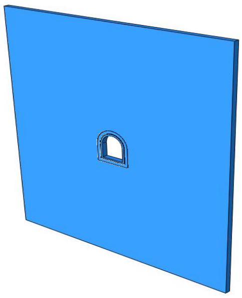

Figure 1. Geometric Model

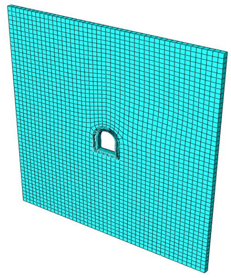

Figure 2. Finite Elemen Model

2.3 Calculation Parameters

According to the test, the values of elastic modulus, cohesive force and internal friction angle parameters of the surrounding rock are taken as shown in Table 1. Concrete damage model, according to the " Hydraulic Concrete Structure Design Code " (SL191-2008) to take the value.

Table 1. Computational Model Parameters

Material Name	Elastic Modulus (GPa)	Poisson's Ratio	Density (kg/m³)	Friction Angle (°)	Cohesion (MPa)
Surrounding Rock	0.3	0.4	2560	31.9	1.75
Initial Support	22	0.2	2500	-	-
Steel Arch Frame	-	-	7800	-	-
Lining	28	0.2	2500	-	-
Equivalent Compression Zone	0.45	0.4	2560	31.9	2.275

3. Numerical Analysis of Tunnel Bearing Capacity Evaluation After Grouting

Defects are mainly concentrated in the top arch of the lining and other locations, these parts may be subjected to both tensile stress and compressive stress, at this time, the lining of the top arch of the lining of the lining of the hollow, not dense often lead to the problem of insufficient lining stiffness of the tunnel.

3.1 Calculation Results of Surrounding Rock After Grouting

Through calculation and analysis, it is found that the maximum main compressive stress in the surrounding rock of the existing hydraulic tunnel after lining cavity before grouting and filling occurs at the bottom position of the surrounding rock, and the maximum deformation in the surrounding rock occurs at the top position of the surrounding rock. Among them, working condition 1 (perimeter rock + primary support + steel arch share 70% of the total load of the surrounding rock, and lining share 30% of the total load of the surrounding rock). The maximum principal compressive stress of the surrounding rock before grouting is 0.6569MPa, and the maximum deformation of the top of the surrounding rock is 7.235mm, while the maximum principal compressive stress of the surrounding rock in Case 2 (the surrounding rock + primaries + steel arch share 50% of the total load of the surrounding rock, and the lining shares 50% of the total load of the surrounding rock) is 0.5165MPa, and the maximum deformation of the top of the surrounding rock is 5.515mm, and the value of plastic shear strain is smaller, which shows that the plastic zone is biased. The value of plastic shear strain is small, which shows that the plastic zone is small.

Through calculation and analysis, it is found that the maximum principal compressive stress value of the surrounding rock after grouting is 0.5638MPa, and the maximum deformation of the top of the surrounding rock is 6.969mm. the maximum principal compressive stress value of the surrounding rock in case 2 (the surrounding rock + primary support + steel arch share 50% of the total load of the surrounding rock, and the lining share 50% of the total load of the surrounding rock) is 0.3347MPa, and the maximum deformation of the top of the surrounding rock is 4.924mm, and the plastic shear strain value is small, showing that the plastic zone is small. The maximum deformation at the top of the surrounding rock is 4.924mm, and the value of plastic shear strain is small, which shows that the plastic zone is small. The value of plastic shear strain is small, which shows that the plastic zone is small. Due to the space reason, only the maximum principal stress of the surrounding rock of the cave chamber in Case 2 is given here as shown in Figure 3, and the principal displacement of the surrounding rock of the cave chamber is shown in Figure 4.

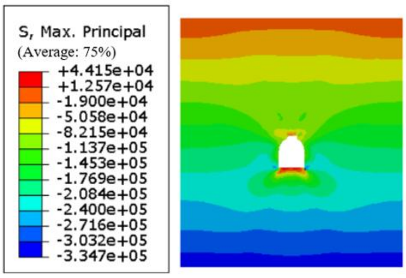

Figure 3. Maximum Principal Stress Cloud Diagram of the Surrounding Rock of the Cave Chamber (unit: Pa)

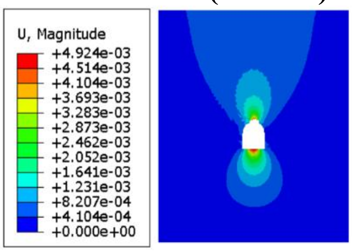

Figure 4. Cloud Diagram of Main Displacement of Surrounding Rock of the Cave Chamber (unit: m)

3.2 Calculation Results of Steel Arch After Grouting

Through calculation and analysis, it is found that the maximum main tensile stress in the steel arch before grouting occurs in the position near the top arch of the steel arch. The maximum deformation of the steel arch occurs near the top of the arch. The maximum main tensile stress is 98.62MPa and the maximum deformation is 10.108mm under working condition I. The maximum main tensile stress is 85.16MPa and the maximum deformation is 7.398mm under working condition II. The maximum main tensile stress occurs near the top arch of the steel arch after grouting. The maximum deformation in the steel arch occurs at the position near the top arch of the steel arch. The maximum principal tensile stress is 75.16 MPa and the maximum deformation is 6.398 mm in Case I. The maximum principal tensile stress is 49.98 MPa and the maximum deformation is 2.16 mm in Case II. The maximum principal stress cloud diagram of the steel arch in Case II is shown in Figure 5, and that of the steel arch is shown in Figure 6.

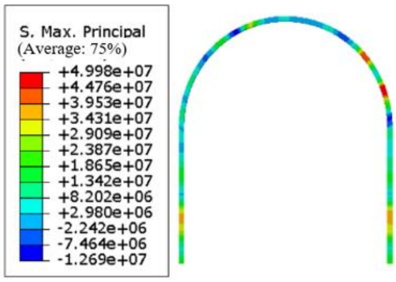

Figure 5. Maximum Principal Stress Cloud Diagram of Steel Arch (unit: Pa)

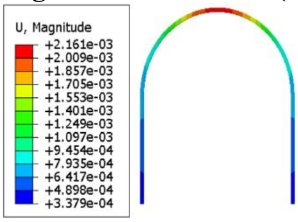

Figure 6. Cloud Diagram of Main Displacement of Steel Arch (unit: m)

3.3 Calculation results of lining after grouting

Through calculation and analysis, it was found that the maximum main tensile stress in the lining appeared in the position near the bottom plate of the lining, and the maximum deformation in the lining occurred in the position near the arch of the lining. The maximum main tensile stress in the lining under condition 1 before grouting is 1.07MPa, which is only 32.5% of the design value of tensile strength of C25 concrete, and the maximum deformation of the lining occurs near the top of the lining arch, with the maximum deformation of 7.87mm. The maximum main tensile stress in the lining under condition 2 is 0.9381MPa, which is only 73.86% of the design value of tensile strength of C25 concrete, and the maximum deformation occurs near the bottom of the lining arch, with the maximum deformation of 7.87mm. The maximum deformation of the lining occurred near the arch of the lining, and the maximum deformation was

5.543mm. after grouting, the maximum main tensile stress in the lining under condition 1 was 0.9152MPa, which only reached 55.5% of the design value of the tensile strength of C25 concrete, and the maximum deformation in the lining occurred near the arch of the lining, and the maximum deformation was 5.68mm. the maximum main tensile stress in the lining under condition 2 was 0.9152MPa, which reached 5.68mm. the maximum main tensile stress in the lining under condition 2 was 0.9152MPa, which reached 5.68mm. The maximum main tensile stress in the lining under Case 2 is 0.9152MPa, which is only 72.06% of the design value of tensile strength of C25 concrete, and the maximum deformation of the lining occurs near the top of the lining arch, with the maximum deformation amount of 4.99mm, which shows that the safety reserve is sufficient, and therefore the reinforcement measures are reasonable and feasible. The maximum principal stress cloud diagram of steel arch for working condition II is shown in Figure 7, and the maximum principal stress cloud diagram of steel arch is shown in Figure 8.

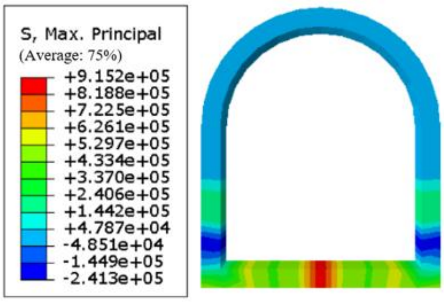

Figure 7. Lining Maximum Principal Stress Cloud (unit: Pa)

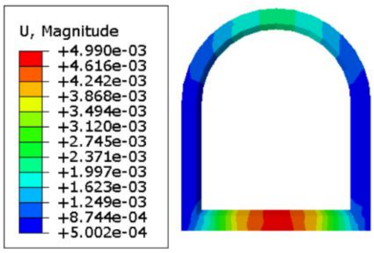

Figure 8. Lining Main Displacement Cloud (unit: m)

To summarize, the results of numerical calculation and analysis of the comparative evaluation of the safety of the tunnel lining in Case I (perimeter rock + primary support + steel arch sharing 70% of the total load of the perimeter rock and lining sharing 30% of the total load of the perimeter rock) and Case II (perimeter rock + primary support + steel arch sharing 50% of the total load of the perimeter rock and lining sharing 50% of the total load of the perimeter rock) after the lining is empty and not compacted and reinforcing, it is found that after grouting and reinforcing of the tunnel lining in Case I (perimeter rock + primary support + It is found that the main tensile stress of the lining in Case 1 (perimeter rock + primary support + steel arch share 70% of the total load of the perimeter rock, and the lining shares 30% of the total load of the perimeter rock) is 0.4564MPa after grouting, and the degree of safety is increased by 64% compared with that of the pre-grouting lining. After grouting reinforcement in Case II (perimeter rock+ primary support+ steel arch share 50% of the total load of the perimeter rock, lining share 50% of the total load of the perimeter rock), the main tensile stress of the lining is 0.9152MPa, and the degree of safety surplus is 27.9% higher than that before grouting, which is lower than that required by the design value of the strength of C25 concrete. Therefore, it can be seen that the defective lining is improved and sufficiently rich in safety after reinforcement.

4. Conclusion

Taking a section of water transfer tunnel in Shaanxi Province as a specific case, a detailed analysis is carried out by using ABAQUS general finite element software through two working conditions, namely, Working Condition I (perimeter rock + primary support + steel arch share 70% of the total load of the perimeter rock, and lining share 30% of the total load of the perimeter rock) and Working Condition II (perimeter rock + primary support + steel arch share 50% of the total load of the perimeter rock, and lining share 50% of the total load of the perimeter rock). A detailed analytical study was carried out using ABAQUS general-purpose finite element software. After grouting reinforcement, it was found that the main tensile stress of the lining in Case I was 0.4564 MPa, and the safety margin increased by 64% compared with that before grouting. The main tensile stress of condition two lining is 0.9152MPa, and the safety margin is 27.9% higher than that before grouting. Therefore, it can be seen that the safety margin of the defective lining was significantly improved after reinforcement. The effect of grouting and filling on the stress distribution and deformation behavior of the cavity after lining was accurately evaluated.

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