

# Comprehensive analysis of surrounding rock stability of diversion tunnel of Pubugou Hydropower Station

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**Abstract:** The geological conditions of the surrounding rock of the diversion tunnel of Pubugou Hydropower Station are complex. In order to review the structural design of the diversion tunnel and the stability of the supporting structure and surrounding rock, the finite element static calculation of the surrounding rock and supporting structure of the diversion tunnel of Pubugou Hydropower Station is carried out. Based on the large-scale finite element software ANSYS, the force calculation is carried out to simulate the ground excavation, diversion tunnel excavation, support and operation. It mainly studies the following aspects: (1) calculation and analysis of initial stress state of diversion tunnel; (2) simulation and calculation of construction excavation and support; (3) lining structure and surrounding rock stress during operation period Strain state analysis.

## 1. Introduction

The Waterfall Ditch Hydropower Station is located in the middle reaches of the Dadu River in Hanyuan County and Ganluo County. The power station hub consists of the gravel soil core rockfill dam, the left bank underground powerhouse system, the left bank open spillway, the left bank flood discharge tunnel, and the left bank venting tunnel and the Niri River water diversion project.

The construction diversion adopts the method of shut-off cofferdam and tunnel diversion. The two diversion holes are arranged on the left bank. The section size of the tunnel is 13×16.5m, the gate hole type and the lining thickness is 1.5m. The 1# diversion tunnel is located on the outside, the inlet elevation is 673.00m, the exit elevation is 668.00m, the length of the cave is 904.00m, the longitudinal slope is 0.00553, and the later slope is converted into a venting hole; the 2# diversion tunnel is located on the inner side, the inlet elevation is 673.00m, and the exit elevation is 668.00m. The length of the hole is 990.00m and the longitudinal slope is 0.00505. The distance between the two holes is 45m. The diversion tunnel size of this project is not large, but the geological conditions of the diversion tunnel, especially the geological conditions of the inlet section, are poor, and the diversion tunnel has a large head during the operation period and the plugging period, especially the plugging period of the 2# diversion tunnel. The external water head is very large (the highest water head is more than 100 meters), and there is no precedent in the projects already built in China.

In order to ensure the stability of the surrounding rock during the construction period and operation period, and optimize the design of the diversion tunnel, this paper takes the diversion tunnel of the Pubugou Hydropower Station as the object, combines the geological and construction materials, and



uses the finite element analysis to design the diversion tunnel. The support structure and surrounding rock stability status are reviewed, and the analysis results have reference significance for similar projects.

## 2. Basic Information

There are two guide holes, which are arranged on the left bank. The 1# diversion tunnel is located on the outside, the inlet elevation is 673.00m, the exit elevation is 668.00m, the length of the cave is 904.00m, the longitudinal slope is 0.00553, and the later slope is converted into a venting hole; the 2# diversion tunnel is located on the inner side, the inlet elevation is 673.00m, and the exit elevation is 668.00m. The length of the hole is 990.00m and the longitudinal slope is 0.00505. The section of the diversion tunnel is a gate type, with a width of 13.00m, a height of 16.50m, and a center angle of the top arch of about 113°.

The full length of the diversion tunnel is compound lining, that is, anchor spray support plus reinforced concrete lining. Within 90° of the reinforced concrete lining vault, backfill grouting is adopted, and the grouting pressure is 0.2 MPa. The surrounding rock of the inlet section of the diversion tunnel is consolidated and grouted with a grouting pressure of 0.5 MPa.

Excavation plan: firstly the diversion tunnel is cut and dig, and then the hole is excavated.

The physical and mechanical parameters of various lithologic surrounding rocks are shown in Table 1, lining concrete C25, and the material parameters are shown in Table 2. The rock formation map is shown in Figure 1.

Table 1 Rock formation physical mechanics parameter

Rock Parameter	Elastic Modulus E (unit:MPa)	Poisson's ratio $\mu$	Density $\rho$ (unit:Mkg/m <sup>3</sup> )
r1	6000	0.27	0.00288
r2	3000	0.27	0.00288
r3	1000	0.30	0.00271
r4	500	0.35	0.0025

Table 2 Concrete lining mechanical parameters

Material	Elastic Modulus E (unit:MPa)	Poisson's ratio $\mu$	Density $\rho$ (unit:Mkg/m <sup>3</sup> )	Tensile Strength	Compressive Strength
C25	23000	0.167	0.002243	1.3 MPa	12.5 MPa

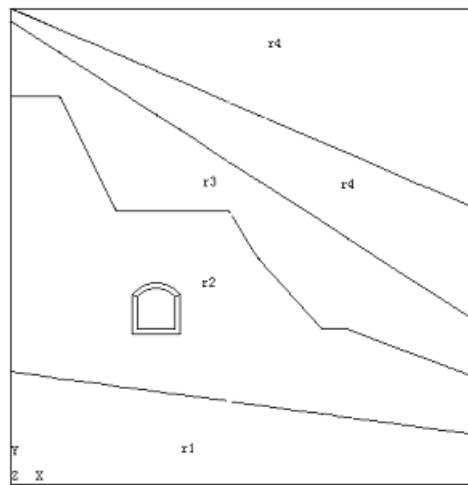


Fig.1 Rock formation boundary

### 3. Calculation Model

#### 3.1. Model Range and Coordinate System

This problem belongs to the plane strain problem. The model range is selected as a 50m long section along the direction of the water flow, and the vertical flow direction is selected from the range of 190m\*191.2m. The model adopts a Cartesian coordinate system. The origin of the coordinate is selected at the center of the lining bottom plate. The direction of the water flow is Z direction, the direction is positive to the downstream, the vertical direction is Y direction, the vertical direction is positive, the horizontal direction is X direction, and the right bank is positive.

#### 3.2. Model Unit and Constraints

The surrounding rock is simulated by SOLID45 eight-node hexahedral element, and the lining is simulated by SOLID45 eight-node hexahedral element. The overall model has a total of 19,460 units. The overall model and the lining model grid are shown in Figures 2 and 3. The two sides of the X-axis of the model and the cross-sections at both ends in the axial direction of the diversion tunnel and the bottom surface exert a normal constraint.

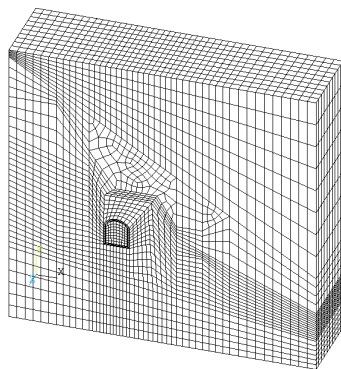


Fig.2 Finite element model

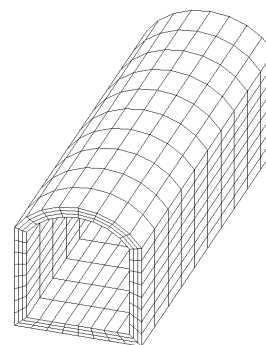


Fig.3 Lining model

### 4. Calculation Process

After the finite element model is established, the solution is solved. The whole solution process is divided into six load steps. The first load step calculates the initial in-situ stress under the self-weight before forming the riverbed appearance, as shown in Figure 4; the second load step calculates the in-situ stress under the self-weight after the current riverbed, as shown in Figure 5; The third step

calculates the surrounding rock stress under the self-weight after open excavation, as shown in Figure 6. The fourth step calculates the surrounding rock stress under the self-weight after the excavation, as shown in Figure 87. The fifth step is to calculate the diversion. The stresses of surrounding rock and concrete after lining and backfilling are shown in Figure 8. The sixth step is to calculate the stress of surrounding rock and concrete under the action of 30m water head and self-weight, as shown in Figure 9.

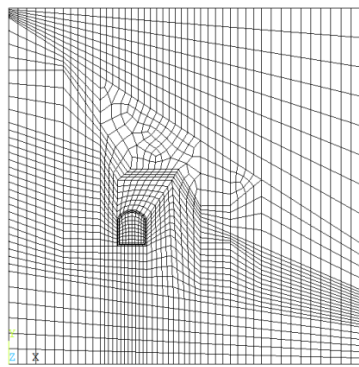


Fig.4 First load step calculation diagram

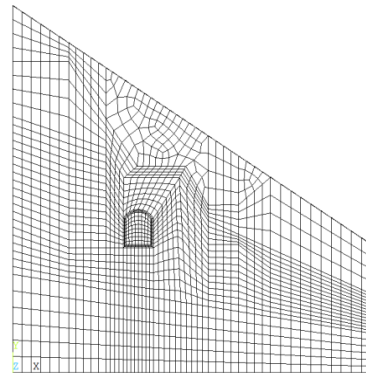


Fig.5 Second load step weathering diagram

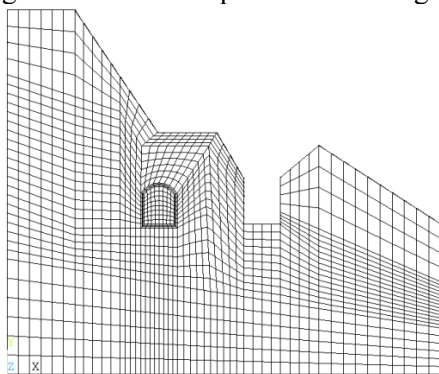


Fig.6 Third load step cut-out diagram

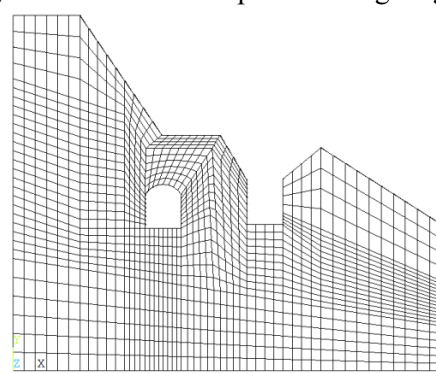


Fig.7 Fourth load step hole cut diagram

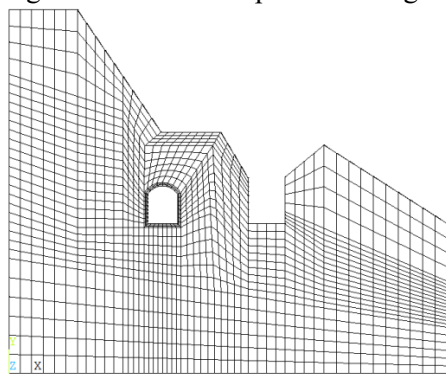


Fig.8 Fifth load step calculation diagram

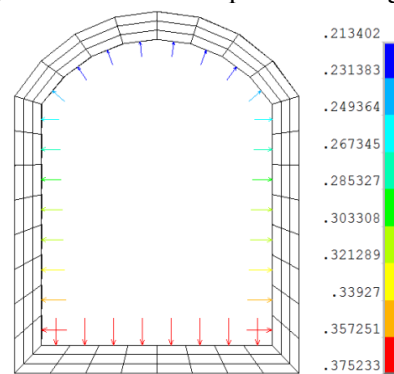


Fig.9 Sixth load step calculation diagram

## 5. Result Analysis

### 5.1. Initial Geostress Field

The initial stress field used in this paper is the self-heavy stress field, and the tectonic stress is not considered. After several years of evolution, the riverbed formed the current riverbed appearance, that is, the result of the second load step calculation is the initial geostress field. Gravity is applied to the overall model. After calculation, the initial stress field distribution state is shown in Figure 10 to

Figure 11. It can be seen from Fig 10 to Fig.11 that the vertical direct stress component is compressive stress, which fully conforms to the law of increasing self-weight stress from top to bottom, and the increasing rate is basically constant. The Z-direction stress range is  $-1.411 \sim 0.0472$  MPa, and the Y-direction stress range is  $-4.775 \sim -0.0647$  MPa. The horizontal stress and the vertical stress ratio are basically equal to 0.3, which is consistent with the Poisson's ratio of the rock.

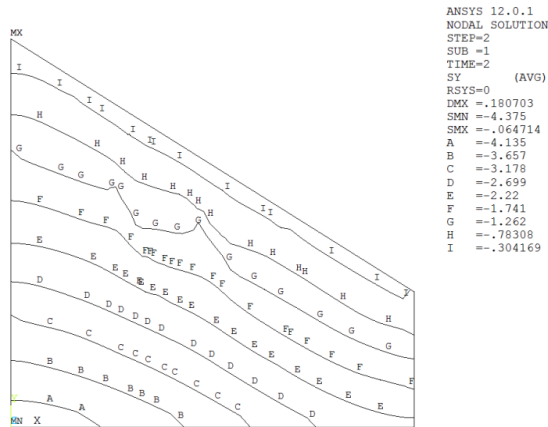


Fig.10 Initial stress field vertical water flow direction (Y-direction) stress map

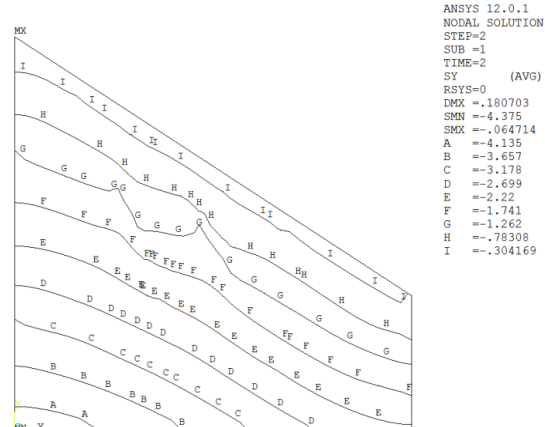


Fig.11 Initial stress field along the water flow direction (Z-direction) stress map

### 5.2. Analysis of Construction Period Results

The construction process includes open excavation of the outer channel, excavation and support of the diversion tunnel.

Open channel excavation, stress changes caused by the release of ground stress, deformation and displacement of rock mass around the excavation. The maximum deformation of rock mass is 0.02919m, and the position is at the top left of the excavation baseline. The whole deformation is almost all vertical deformation, and the X and Z displacement values are almost zero. The rock mass is mainly subjected to compressive stress and the maximum compressive stress is 3.813. MPa. See Figure 12 ~ 16 for details.

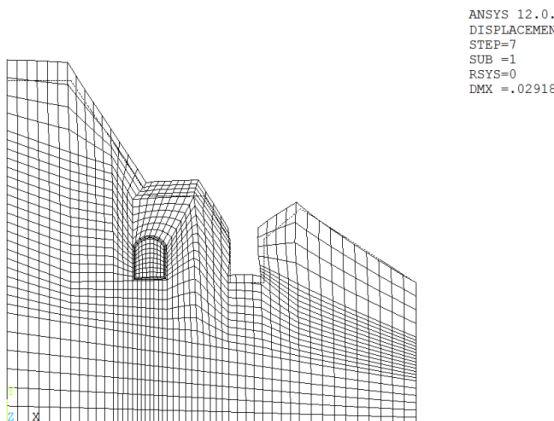


Fig.12 Rock deformation map after open channel excavation

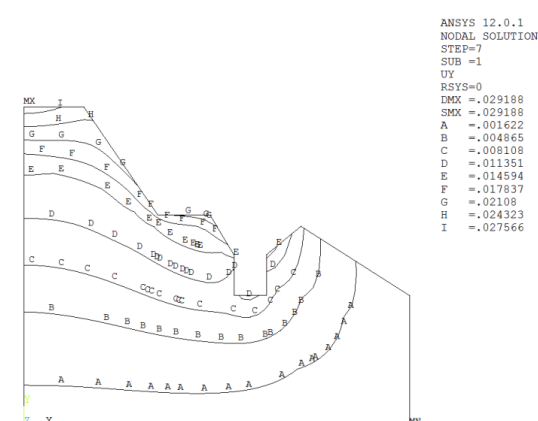


Fig.13 Y-displacement diagram of rock mass after open channel excavation

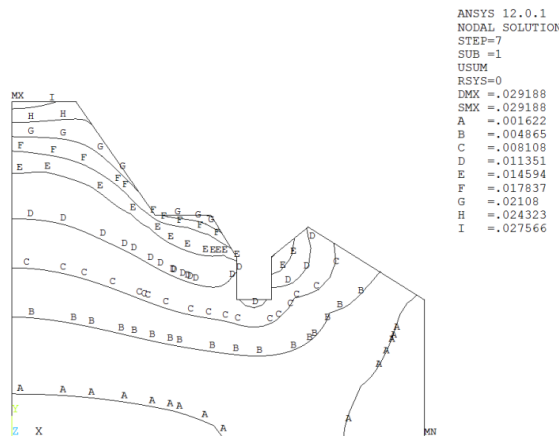


Fig.14 Total displacement of rock mass after open channel excavation

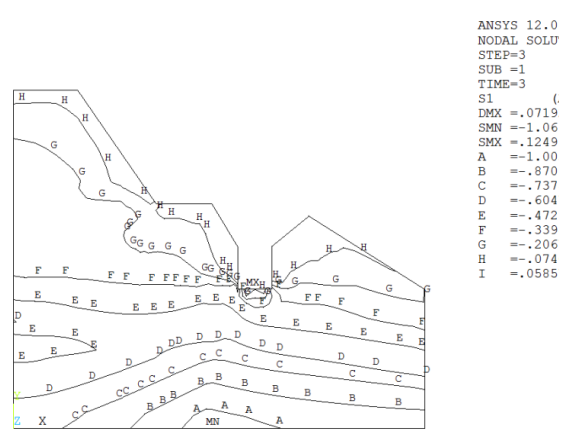


Fig.15 First principal stress diagram of rock mass after open channel excavation

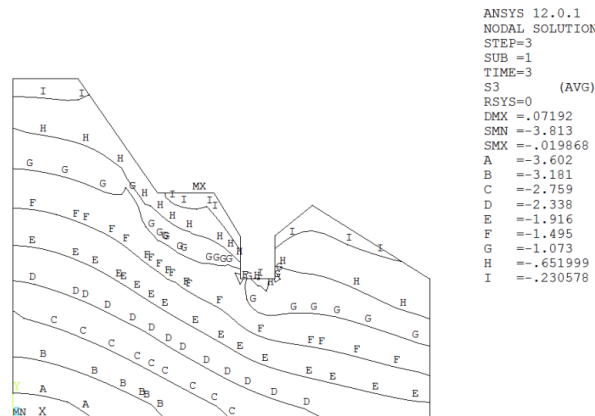


Fig.16 Third principal stress diagram of rock mass after open channel excavation

The excavation of the diversion tunnel is caused by the release of the ground stress, which causes the change of the rock stress state around the hole and induces deformation towards the inside of the hole. The maximum deformation of surrounding rock is 0.02772m, and the position also appears on the left side of the open cut baseline. The whole deformation is almost all vertical deformation, and the X and Z displacement values are almost zero. The surrounding rock is under pressure and the maximum pressure. The stress is 5.492 MPa. See Figure 17to 21 for details.

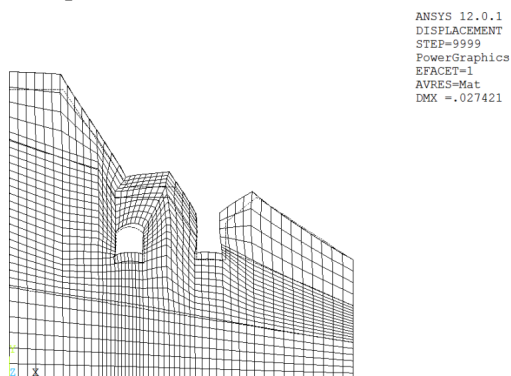


Fig.17 Deformation of surrounding rock after tunnel excavation

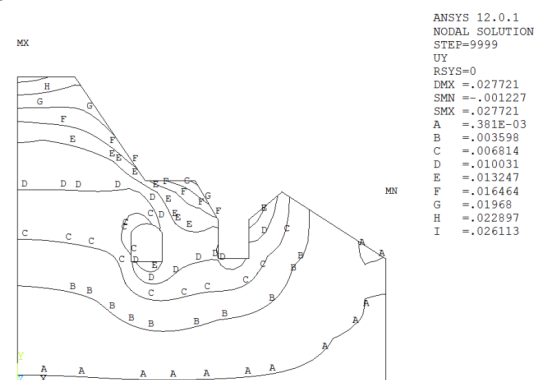


Fig.18 Y-displacement diagram of surrounding rock after tunnel excavation



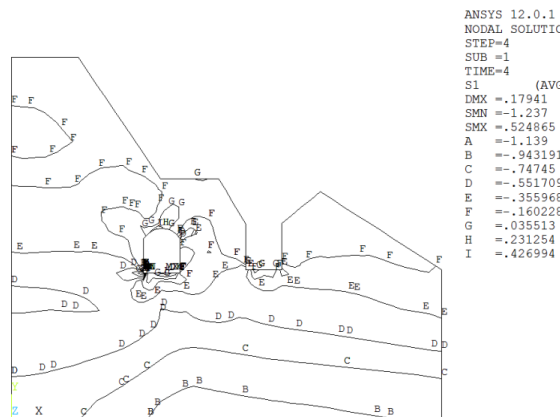


Fig.19 Total displacement map after hole excavation

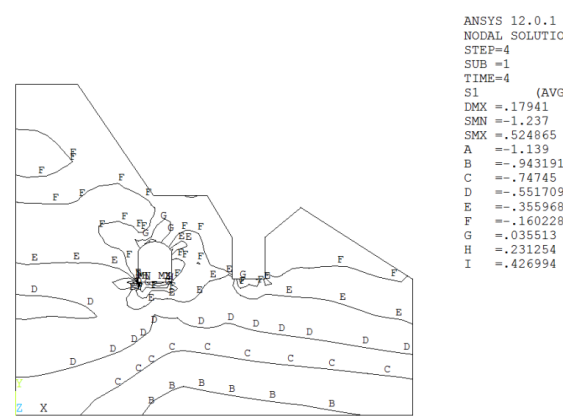


Fig.20 first principal stress map after hole excavation

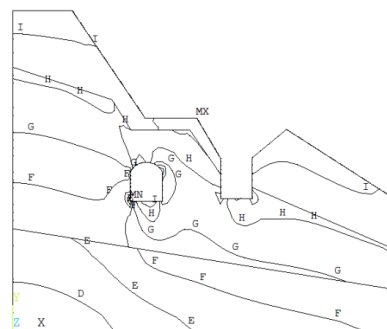


Fig.21 Third principal stress map after hole excavation

After backfill grouting of lining and vault the deformation, stress and displacement of surrounding rock has not changed much. The lining is mainly displaced under gravity and grouting pressure, and its combined displacement is greatly deformed at the vault. The maximum value in the middle of the vault is 0.0016m. The whole deformation is almost all vertical deformation, and the X and Z displacement values are almost Zero, and no plastic zone appeared; the lining concrete showed tensile stress but its value was not large, and the maximum compressive stress was 1.146MPa. See Figure 22~27 for details.

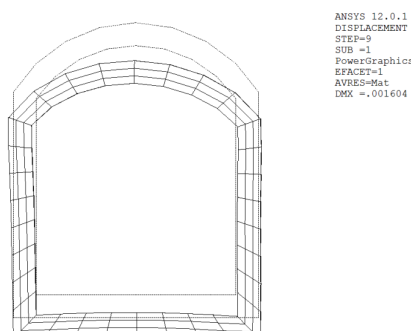


Fig.22 Deformation diagram of lining after lining grouting

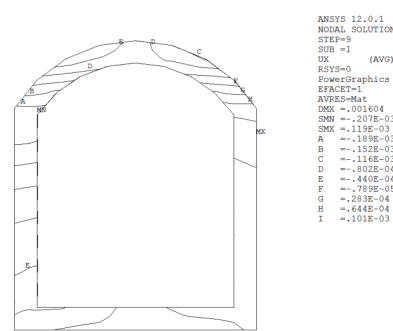


Fig.23 X-direction displacement diagram of lining after lining grouting

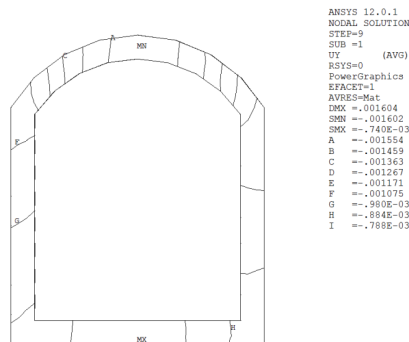


Fig.24 Y-displacement diagram of lining after lining grouting

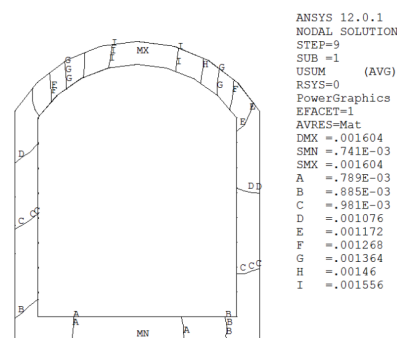


Fig.25 Total displacement diagram of lining after lining grouting

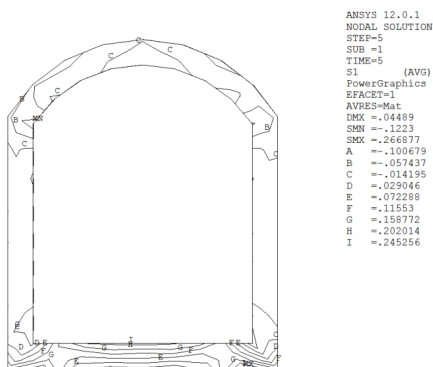


Fig.26 First main stress diagram of lining after lining grouting

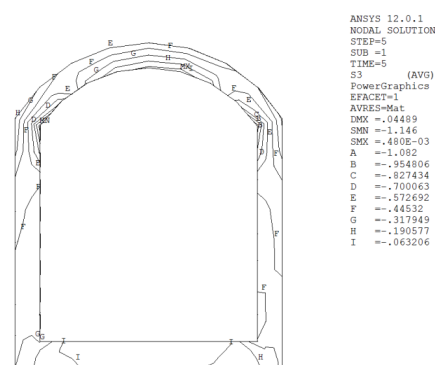


Fig.27 Third principal stress diagram of lining after lining grouting

### 5.3. Runtime Result Analysis

During the operation period of the diversion tunnel, water pressure acts on the inner surface of the lining. The lining and surrounding rock jointly bear the internal water pressure, and the lining and surrounding rock are deformed toward the outside of the cave. The lining concrete is mainly in the tension state. The head of the operation period is taken as 30m. During the operation period, the large displacement of the lining joint occurred in the middle of the bottom plate and the waist of the side wall, and the maximum value was 0.001164m. The larger value of the X-direction deformation of the vertical water flow appears in the waist of the side walls, and the maximum value of the deformation on the left and right sides is 0.001152m; the maximum value in the Y direction is 0.001149m, which appears at the bottom of the lining. See Figures 28 to 31 for details.



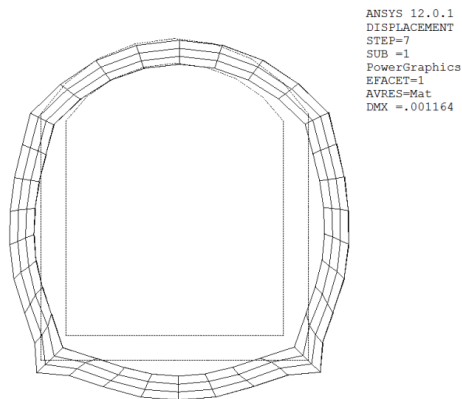


Fig.28 Lining deformation diagram during operation

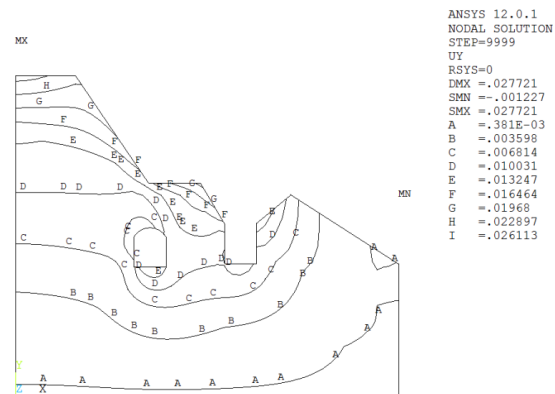


Fig.29 Lining X-direction displacement diagram during operation

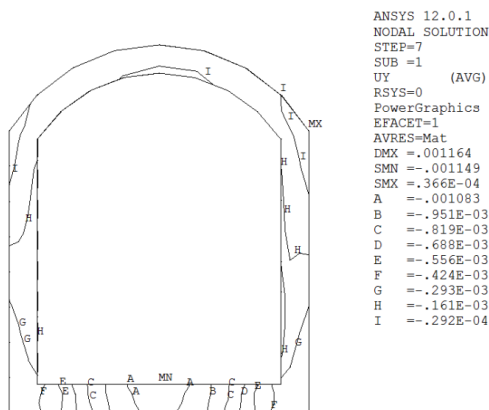


Fig.30 Lining Y-displacement diagram during operation

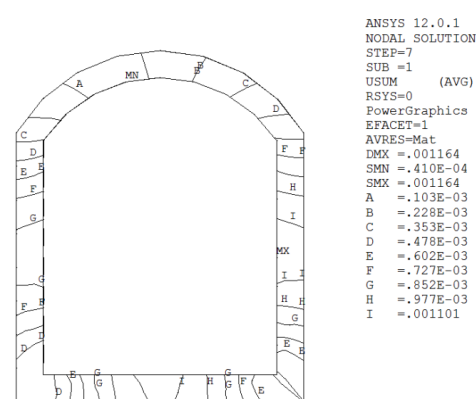


Fig.31 Total displacement diagram of running lining

The maximum tensile stress value of the lining during operation is 3.131 MPa, which appears at the junction of the tunnel side wall and the floor, while the design tensile strength of C25 concrete is 1.30 MPa. Therefore, judging from the tensile stress value and distribution area of the lining, the structure of the lining may have a certain range of cracking area during operation, which affects the normal operation of the tunnel. It is necessary to configure the opening and expansion of the steel to control the crack. See Figures 32 to 33 for details.

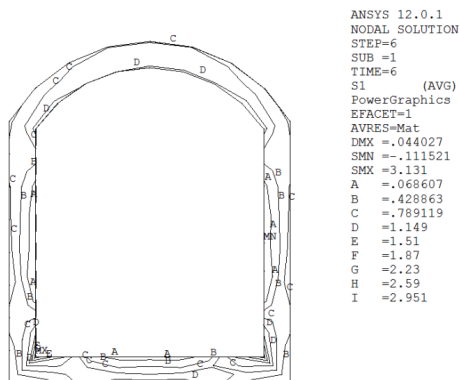


Fig.32 First main stress diagram of the lining during operation

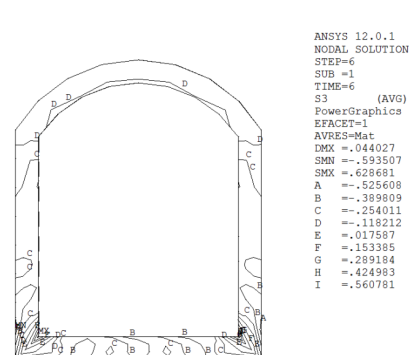


Fig.33 The third principal stress diagram of the lining during operation

## 6. Conclusions

(1) During the construction period, due to the excavation of the diversion tunnel, the ground stress is released and the surrounding rock is under pressure. After backfilling and lining of the lining and arch, the deformation and displacement of the surrounding rock do not change much, and the change of stress is not large.

(2) During the operation period of the diversion tunnel, the water pressure acts on the inner surface of the lining. The lining concrete is mainly in the tension state. The lining structure may have a certain range of cracking area, which affects the normal operation of the tunnel. It is necessary to configure the opening and expansion of the steel to control the crack.

## Acknowledgments

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