Research on the Stability and Support Effect of Earth Section of Hydraulic Tunnel Based on FLAC 3D

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Abstract. The stress of the surrounding rock of hydraulic tunnel can produce a stress load on the lining body, which may cause the crack failure of the lining. The distribution and deformation characteristics play a key role in ensuring the long-term stability of tunnels. Therefore, an analysis of the distribution characteristic is of great significance. This paper takes the branch tunnel in the Yellow River Diversion Project of central Shanxi as an entity for modeling, and uses the finite difference program FLAC3D for analysis and calculation. The research results show that before the support is strengthened, the compressive stress of feet-lock bolts has exceeded the compressive strength of the bolts, with obvious stress concentration at the arch feet; the deformation mainly occurs on the vault and the bottom plate; after strengthening the support, the deformation of the steel arch prop, the axial force of the steel arch prop, and the maximum tensile stress of the anchor rods are all reduced. The stable support effect can meet the requirements of construction and later operation.

Keywords: Hydraulic tunnel, surrounding rock stability, support effect.

1. Project overview

The Yellow River Diversion Project in the central part of Shanxi Province includes the water intake project and the water transfer project. The designed water intake flow is 23.55m3/s, and the designed pump lift is 200.0m; the total installed capacity is 96,000 kilowatts, and the total length of the water transfer line is 384.5km. One of the construction adits of the project has a total length of 450m and a longitudinal slope of -10.2%. The geological conditions of the tunnel barrel are as follows: the ground elevation is 1032~1172.5m, the depth of the tunnel bottom is 18.2~100m, the surrounding rocks of the tunnel include the Q_3^{eol} low liquid limit silt, N2 low liquid limit clay as well as calcareous nodule layer, marl, sand and gravel layers, and the groundwater is below the bottom of the tunnel. The N2 low liquid limit clay has a density of 1.80~1.93g/cm3, a dry density of 1.62~1.68g/cm3, a water content of 11.2~15.5%, a void ratio of 0.604~0.668, and compressibility of 0.12~0.15MPa-1, which is low compressibility. The cohesive force of natural shear strength is 15.2kPa, and the internal friction angle is 19.0o. The surrounding rock of the tunnel is a loose layer and cannot maintain homeostasis. The geology of the project is classified as Class V.

2. Calculation description

2.1 Section

According to the provided geological section map and the geological data collected on site, a representative section (the most dangerous section in the rock category) , Section 1-1, is selected, as shown in Fig 1. It is located in an earth cave with a buried depth of about 100m.

2.2 Calculation parameters

2.2.1 Mechanical parameters of rock and soil

The geostress field is dominated by geostatic stress, and the lateral pressure coefficient is taken as 0.6-0.8 based on engineering experience. The surrounding rock is assumed to be the elastoplastic material, and the Moore-Coulomb model is used as the constitutive model. In the calculation process, the physical and mechanical parameters shown in Tables 1 and 2 are used for calculation, and the parameter values of surrounding rock are taken by referring to "Road Tunnel Design Rules JTG/T D70-2010".

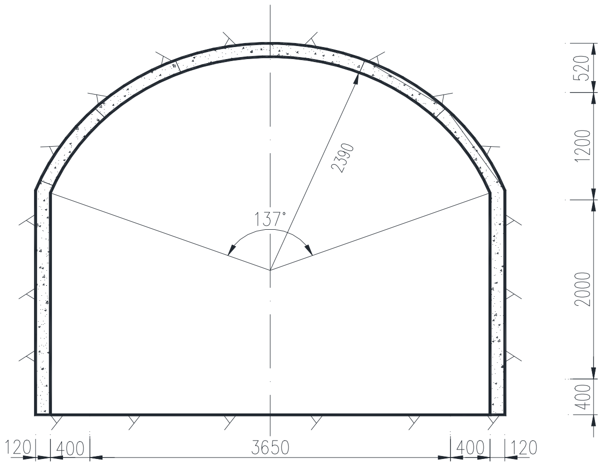

Fig. 1 Cross section of earth section (section 1-1, unit: mm)

Table 1. Rock and soil mechanical parameters for the calculation

Surrounding rock category	Density (kg/m^3)	Modulus of deformation E(GPa)	Cohesion force C（MPa）	Friction angle φ（°）	Poisson's ratio μ
low liquid limit clay	2000	0.02	0.045	22	0.35

2.2.2 Support parameters

Table 2. Mechanical parameters of support

Materials	Modulus of deformation E（GPa）	Poisson's ratio μ	Density (kg/m^3)
Steel arch prop	200	0.3	7850
Anchor rod	20	0.3	7850
Shotcrete	21.0	0.2	2200
Slab Concrete	28.0	0.2	2400

2.3 Calculation methods and models

In the calculation, the finite difference program FLAC3D is used for numerical simulation analysis. The FLAC3D software can well simulate the tunnel excavation and support design, and contains a wealth of constitutive models, which can well simulate the role of support structures such as anchor rod, spray layer, lining, etc., and can meet the needs for evaluating tunnel support stability[1-4]. The meshing diagram of FLAC3D model is shown in Fig 2.

In this calculation, the built-in beam element of FLAC3D [5-9] is used to simulate steel arch prop, the anchor rod element is used to simulate the anchor rod and feet-lock bolt of the system, and the shell element is used to simulate the concrete spray layer and slab concrete. The contribution of connecting bars and steel meshes to Shotcrete's mechanical properties is not considered as a safety reserve. Therefore, according to the elasticity formula provided by FLAC3D[10-11], we can obtain

There are 17,703 nodes and 15,552 elements in this calculation model. The tunnel axial direction, horizontal-right direction, and the vertical upward direction are taken as the Y axis, the positive direction of the X axis, and the Z axis, respectively.

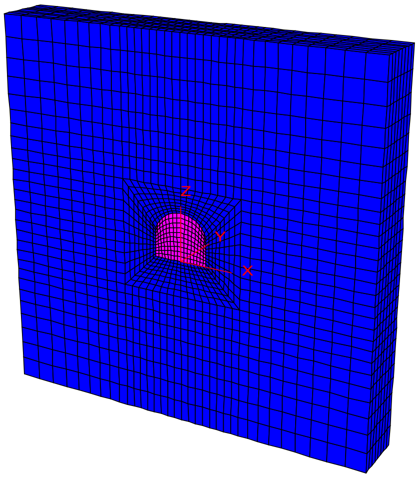

Fig 2. Meshing diagram of FLAC3D model

3. Analysis and support mode

3.1 Parameters and results

The earth section adopted is section 1-1, the general support parameters adopted are shown in Table 3, and the support strengthening parameters adopted are shown in Table 4. The calculation results of FLAC3D using formulas 1 and 2 are shown in Table 5.

Table 3. Support parameters adopted for calculation

Steel arch prop model	I14a
Steel arch prop spacing (m)	1.2
Longitudinal spacing of system anchor rods (m)	1.2
Circumferential spacing of system anchor rods (m)	1
Shotcrete thickness (mm)	270
Slab Concrete thickness (mm)	350

Table 4. Support parameters adopted for calculation

Steel arch prop model	I20
Steel arch prop spacing (m)	**0.6**
Longitudinal spacing of system anchor rods (m)	**0.6**
Circumferential spacing of system anchor rods (m)	1
Shotcrete thickness (mm)	**400**
Slab Concrete thickness (mm)	400

Table 5. Calculation results of FLAC3D

Calculated section	Maximum vault settlement（mm）	Maximum floor heave（mm）	Maximum horizontal deformation of side wall（mm）	Maximum vertical displacement of steel arch prop vault（mm）	Maximum horizontal deformation of steel arch prop column（mm）	Maximum axial force of steel arch prop（kN）	Maximum tensile stress of the system anchor rod（MPa）	Maximum compressive stress of feet-lock bolt（MPa）
1-1	118	128	36.1	82	17.3	915.8	120.7	334.6
1-1（Support strengthened）	89	95	21.1	61	10.3	568.2	70.79	217.2

3.2 Analysis

When the buried depth of the Earth Section is 100m, if the spacing of steel arch props adopted for the support is 1.2m , the longitudinal spacing of the system anchor rods is 1.2m, and the Shotcrete thickness is 0.27mm, there appear large vertical and horizontal deformations during excavation according to the results, which possibly causes the instability of the tunnel; the compressive stress on the foot-lock bolt has exceeded the compressive strength of the anchor rod, which may cause the Steel arch prop to sink or tilt excessively, although it is assumed that the support interval is short in this calculation.

If the steel arch prop spacing and the longitudinal spacing of system anchor rods are reduced from 1.2m to 0.6m, and the Shotcrete thickness is increased to 400mm, the maximum vault settlement can be reduced from 118mm (↓) to 89mm (↓), and the maximum tensile stress of system anchor rods can be reduced from 120.7MPa to 70.79Mpa, and the maximum compressive stress of the feet-lock bolt can be reduced from 334.6MPa to 217.2MPa. The steel arch prop, the steel arch prop axial force and the maximum tensile stress of the anchor rod have all been reduced, and the steel stress of the foot-lock bolt is still large.

3.3 Supporting method used in construction

According to the analysis, the supporting methods adopted for the tunnel are as follows:

1. An expansion and settlement joint is set up every 8m along the barrel in the lining section. The joints above the groundwater level are filled with polyethylene foam board, and the 651 type rubber waterstop is set below the groundwater level after the joints are filled with polyethylene foam board.

2. The support uses shotcrete with mesh reinforcement, with C20 concrete sprayed with a thickness of 120mm. The steel bar for the mesh is φ8 steel bar, with the mesh size 200mm×200mm. The φ20 random anchor rods (L=2m) are arranged in the umbrella arch (133°). According to the geological situation, 20a type steel arch prop support is randomly laid out, and advanced anchor rod or advanced small pipe grouting technology is set within the top arch before excavation, of which the advanced anchor rod is φ25@400, with a length of 3m each, and the steel pipe of advanced small pipe (steel pipe with hole) is φ42 hot-rolled steel pipe with wall thickness 3.0mm. The pipe shed is arranged in the top arch, with a single steel pipe length of 5m and a steel pipe spacing of 0.4m. The drilling direction and the hole axis are at an angle of 3°, deviating to the outside of the hole. The overlap length is 1.5m, and the tunnel face is exposed for 0.5m. The pipe shed is welded with the lower transversely erected steel arch prop (or steel grating). The grouting material used is

cement slurry (chemical material is used when water plugging is required), with grouting pressure not higher than 0.2MPa.

3. The support methods and support sections are adjusted according to the geological conditions and actual conditions during construction.

4. The concrete strength grade of the tunnel lining is C25, and the impermeability grade is W4.

5. The tunnel is backfill grouted within 100° of the top arch, with a grouting pressure of 0.2MPa.

6. The "SL377-2007 Technical Specification for Shotcreting Support for Water Conservancy and Hydropower Engineering" and "SL378-2007 Construction Specification for Underground Excavation Engineering of Hydraulic Buildings" are strictly implemented during construction.

3.4 Support effect

The above-mentioned support method was adopted in the construction, and it passed safely. The later safety monitoring data show that there is no deformation and settlement occurred. The supporting effect is shown in Fig 3. The supporting effect is stable and the support can meet the requirements of construction and later operation.

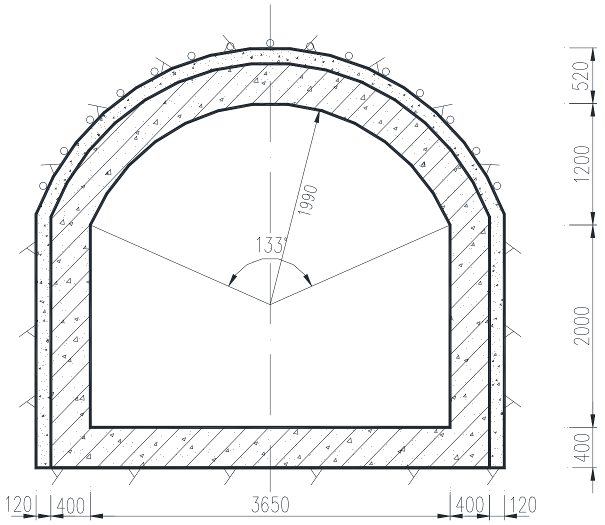

Fig.3. Cross section of earth section (Section 1-1 support, unit: mm)

4. Suggestions

In locations where the burial depth is large, because there is a severe collapse of the surrounding rock, the steel arch prop support spacing and the system anchor rod spacing should be appropriately reduced for the position with relatively large clearance convergence. In addition, the support should be completed as soon as possible to improve the stress of Steel arch prop and anchor rod and reduce the deformation of surrounding rock. (2) In the tunnel section with a large clearance convergence, in order to maintain the thickness of the tunnel lining structure and the net size of the tunnel, additional blocks can be added at the top and bottom of the steel arch prop as the reserved deformation for the clearance convergence. (3) Due to the soft floor of the soil tunnel, the steel arch prop footing is prone to sinking, resulting in greater deformation of the vault and greater compressive stress on the foot-lock bolt. Therefore, it is suggested to dig out the softness, pour cushion blocks or set steel cushion plates and increase the amount of grouting for the feet-lock bolt before installing the steel arch prop column.

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