Construction mechanical effect of highway tunnel with four lanes in layered rockmass

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Abstract: Jiangshuiquan tunnel was a highway tunnel with four lanes. Its maximum excavation cross section was 170.1 m² in Class III surrounding rock. The host rock was horizontal layered limestone, and it have obvious transverse isotropy. Based on laboratory experiments and site survey of rockmass structure, mechanical parameters of rockmass were determined. Numerical simulation and field test were used to study the deformation and failure characteristics of tunnel, pressure of surrounding rock, stress of shotcrete and lattice girder. It was concluded that lateral elasticity modulus of rockmass was obviously bigger than vertical elasticity modulus. Settlement of vault was the main deformation form of surrounding rock. Rock-falling in spandrel and delaminating collapse of roof were the common failure phenomenon. Setting rock bolt in vault was necessary in horizontal layered rockmass. Compared with other positions, pressure of surrounding rock, stress of shotcrete and steel frame of the vault were relatively small.

1. Introduction

Sedimentary rock with stratified structure was widely distributed in China. And it account for 77.3% land area. Because of obvious stratification, strength and deformation behaviour of layered rockmass appear remarkable transverse isotropy. Deformation and failure mechanism of layered rockmass was also different with other types of rockmass[1].

Model test, numerical simulation and in-situ test could be used to study deformation and strength behaviour of layered rockmass. In model test, layered rockmass were simulated by matching of similar materials and combination. And then loading test was carried out to ascertain its mechanical property. In numerical simulation, elastic theory of transverse isotropy was already satisfactorily employed to account for anisotropy of rock. Its stress-strain relationship was determined by five independent deformation constants. While strength anisotropy was considered, corresponding failure criterion need to be established. Scholars had studied the anisotropy, failure mode of layered rockmass and optimization of support parameters by means of theory and experiment.

JC Jaeger[2] lucubrated rock strength anisotropy of Coulomb-Navier failure criterion in plane theory. YANG Junsheng[3], ZUO Shuangying[4] had studied the failure mode and criterion of layered rock, and further tested it. Anisotropy and elastoplastic deformation behaviour of layered rockmass were also studied by numerical simulation[5~8]. ZHONG Fangping, et al[9~10] had optimized design of rock bolt according to deformation and failure of layered rock.
Because of the difference of orientation, thickness and feature of weak plane, mechanical response during tunneling under different engineering condition were different. Jiangshuiquan highway tunnel were a four-lanes tunnel. Its excavation span was 19.2m, and its excavation area was 170.1m². Surrounding rock of tunnel are mainly horizontal layered limestone. By means of finite element software Midas GTS NX, deformation and plastic zone of layered rockmass were analyzed during tunneling. Based on stress analysis of support structure, construction method and suitable support parameters were determined. This measures could insure tunneling rapidly and safely.

2. Brief Introduction of Engineering

Jiangshuiquan tunnel was located in Lixia district of Jinan city, Shandong Province. The tunnel was consisted of two separate holes. And the distance between two holes was 14~31 meter. Design speed of tunnel was 80km/h. Left hole was 3.1km long, and the right hole was 3.085km long. Surrounding rockmass of tunnel was moderately weathered limestone with medium-thick bed. Bedding of limestone was closed, and no filling as shown in Figure 1. Classification of surrounding rock were mainly Ⅲ~Ⅴ. Surrounding rock situated between YK3+700 to YK3+780 was grade Ⅲ. And the burial depth was almost 94m. There were two sets of rock joint. Its occurrence was steep, and bond between adjacent joints was poor.

![Figure 1 Horizontal medium-thick layered limestone](image)

3. Mechanical parameters of rock mass

3.1 Mechanical test of rock

According to structure of rock mass, rock samples were made along two orthogonal directions, that is parallel and perpendicular to bedding of rock. Two kinds of samples were shown in Figure 2 ~3.

![Figure 2 Rock sample perpendicular to bedding](image) ![Figure 3 Rock sample parallel to bedding](image)
Three specimens of every kinds of sample were chosen to conduct uniaxial compression experiment. Elasticity modulus and poisson of rock in two directions were acquired. Elasticity modulus \((E_v)\) and poisson \((\mu_v)\) perpendicular to bedding were respectively 4.37GPa and 0.24. Elasticity modulus \((E_h)\) and poisson \((\mu_h)\) parallel to bedding were respectively 5.26GPa and 0.27.

### 3.2 Mechanical parameter of rock mass

Gardner[11]、Lianyang ZHANG[12] proposed the empirical relationship between deformation modulus of rockmass \((E_m)\) and elasticity modulus of rock \((E_e)\), such as formula (1).

\[
E_m = \alpha_E E_e \quad (1a)
\]

\[
\alpha_E = 0.0231 RQD - 1.32 \geq 0.15 \left( RQD > 57\% \right) \quad (1b)
\]

\[
\alpha_E = 0.15 \left( RQD < 57\% \right) \quad (1c)
\]

\(RQD\) were determined by field geological survey. \(RQD_v\) perpendicular to bedding of rock mass were 80% and \(RQD_h\) parallel to bedding of rock mass were 89%. Deformation modulus of rock mass in two directions were respectively 2.31GPa \((E_{mv})\) and 3.87GPa \((E_{mh})\) by substituting \(RQD\) into formula (1).

Shear strength of rockmass were obtained by in-situ shear test, cohesion \((C)\) is 0.44MPa and internalfrictionangle \((\phi)\) is 40°.

Other deformation index of rockmass with transverse isotropy were determined by synthesized structure of rockmass and Code for Design of Road Tunnel[13]. Vertical possion of rock mass \((\mu_v)\) is 0.27, and horizontal possion of rock mass \((\mu_h)\) is 0.30. Shear modulus of rockmass \((G)\) is 1.16GPa. Physical and mechanical parameters of horizontal layered rockmass were listed in Table 1.

| Rockmass of Grade III | Density \(\gamma (\text{kN}\cdot\text{m}^{-3})\) | Elasicty modulus \(E_{mv}/\text{MPa}\) | Elasicty modulus \(E_{mh}/\text{MPa}\) | Possion \(\mu_{mv}\) | Possion \(\mu_{mh}\) | Shear modulus \(G/\text{GPa}\) | Cohesion \(C/\text{MPa}\) | Internal friction angle \(\phi/°\) |
|-----------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Horizontal layered rockmass | 24.0 | 2.31 | 3.87 | 0.27 | 0.30 | 1.16 | 0.44 | 40 |

### 4. Section shape and support parameters of tunnel

Composite lining without inverted arch adopted in rockmass of Grade III was shown in Figure 4. Primary support was C25 shotcrete with 20cm thick. Lattice girder of 140×160@120cm were set inside shotcrete. Secondary lining was C30 molded reinforced concrete with 50cm thick. Rebar of φ25@20cm were symmetrically embedded in lining. Detailed support parameters were listed in Table 2.
Figure 4 Section of tunnel in Grade III (units: cm)

Table 2 Parameters of support structure of tunnel

| Thickness of shotcrete /cm | Rebar mesh | Grouted rock bolt | Space of lattice girder /m |
|---------------------------|------------|-------------------|---------------------------|
|                           | Position   | Diameter /mm      | Mesh size /cm              |
|                           |            |                   |                           |
| 20 (C25)                  | Vault, wall| φ8                | 20×20                      |
|                           | vault      | 250(Φ20)          | 100×100                    |
|                           |             | 40×160            | 50cm C30 concrete          |
|                           |             | @120cm            | @20 cm                     |

5. Simulation of construction process of tunnel

5.1 Numerical model
According to actual engineering condition, 3-D numerical model was 108m long, 108m wide and 148m tall. The tunnel was in the middle of model. Numerical simulation range was corresponding to YK3+700~YK3+808. Normal displacement constraint were applied to other five boundaries except upper free boundary.

Surrounding rock were simulated by hexahedral element with eight nodes. Primary support was simulated by plate element. The model was composed of 120420 elements and 127551 nodes. 3-D numerical model was shown as Figure 5.

5.2 Simulation of excavation and support
Two bench construction scheme was adopted in tunneling. Upper bench was 8.36m high and 54m long. Lower bench was 2.4m high. Cyclic advance was 3.6m. Considering strength growing rule of shotcrete and different construction schedule of combined support, support effect could not get into work quickly. In numerical simulation, support was set lagged behind one excavation cycle.

5.3 Simulation of excavation and support
Horizontal layered rockmass was regarded as elastic-plastic medium with transverse isotropy. And it followed M-C yield criterion. It was simulated by Joint Model in MIDAS GTS. Shear failure was supposed to preferentially occur along bedding plane. Primary support was regarded as linear elastic isotropic medium. Equivalent elastic modulus of primary support was 23.37GPa, possion was 0.2, and density was 2200kg/m³.
6. Distribution of displacement and stress of surrounding rock and support stress

Monitoring plane was supposed in the middle of model to eliminate the boundary effect. Deformation of surrounding rock and stress of primary support during construction were analyzed.

6.1 Displacement of surrounding rock

Monitoring projects of deformation of surrounding rock were settlement of vault and horizontal convergence, shown in Figure 6. Deformation curves of surrounding rock and key positions around tunnel were shown in Figure 7~9.

It could be seen that vertical deformation of upper surrounding rock presented noliner distribution. Maximum vertical deformation was located in vault, and the value was 1.64cm. Horizontal deformation of surrounding rock also presented noliner distribution. Maximum horizontal deformation was located in arch foot, and maximum horizontal convergence was 5.6mm. Settlement of vault was much bigger than horizontal convergence. It could be concluded that settlement of vault was mainly deformation in horizontal layered rockmass.

6.2 Stress of surrounding rock

Taking upper surrounding as an example, tangential stress above vault presented linearly increasing trend, as shown in Figure 10. Hoop stress around tunnel were biggest, and was compressive stress. Maximum hoop stress was -2.2MPa. Radial stress of surrounding rock presented noliner distribution, as shown in Figure 11. Minimum radial stress emerged around tunnell, and was compressive stress. Minimum radial stress was -51.7kPa. So maximum stress difference emerged around tunnel, and the most easily damaged position was the hole wall.
6.3 Stress of primary support

Maximum and minimum stress contour of primary support were shown in Figure 12–13. Maximum stress of support was 6.7MPa, and it was tensile stress. Maximum stress was located in vault of support. Minimum stress of support was -1.34MPa, and it was compressive stress. Minimum stress was located in arch foot of support.

During tunneling, maximum tensile stress was gradually increasing. Tensile stress of vault support was biggest, and it was easy to damage.

Figure 7 Contour of vertical deformation of surrounding rock (m)

Figure 8 Contour of horizontal deformation of surrounding rock (m)

Figure 9 Deformation curve of surrounding rock during tunnelling

Figure 10 Distribution of tangential stress of host rock

Figure 11 Distribution of radial stress of host rock
7. Plastic zone of surrounding rock
To analyse the plastic zone of surrounding rock and parameters of rock bolt, plastic zone of rock when setting rock bolt in vault or not were compared. Numerical simulation results were shown in Figure 14~15.

The following conclusion could be drawn from the plastic zone of surrounding rock.① Plastic zone of tunnel in horizontal layered rockmass were mainly distributed in vault and bottom of tunnel near side wall. So rock block would fall down from arch shoulder, and stratum delaminating would occur in vault during tunneling.② Maximum depth of plastic zone without rock bolt was 2m. So it was suitable and necessary that setting 2.5m long rock bolt in vault.③ Plastic range in vault would remarkably decreased and stability of tunnel was observably enhanced when setting rock bolt in vault.

8. In-situ test of stress of support structure
To evaluate the rationality of parameters of support structure in Grade III rockmass, monitoring section was choosed in YK3+760. Burial depth of tunnel was 94m. Test projects included pressure of surrounding rock, hoop stress of shotcrete and stress of lattice girder. Monitoring points were shown in Fig.16. Test components were installed on February 14, 2017.

Field test results were shown in Figure 17~19, and measured data were listed in Table 3.
Figure 16 Layout of monitoring points

Figure 17 Distribution of pressure of surrounding rock (MPa)

Figure 18 Distribution of hoop stress of shotcrete (MPa)

Figure 19 Stress distribution of lattice girder (MPa)

Table 3 Field test result of pressure of surrounding rock and stress of support

| Items                        | Pressure of surrounding rock /MPa | Stress of shotcrete /MPa | Stress of lattice girder /MPa |
|------------------------------|----------------------------------|--------------------------|-------------------------------|
| Maximum value                | 0.15                             | -5.32                    | -14.8                         |
| Minimum value                | 0.02                             | -0.55                    | -8.9                          |
| Average value                | 0.068                            | -3.26                    | -7.90                         |
| Position where maximum value emerged | Spandrel                      | Middle of wall           | Spandrel                       |

Pressure value of surrounding rock were between 0.02MPa and 0.15MPa as shown in Figure 17. In general, pressure value were relatively small. Maximum value was 0.15MPa, and it was located in right arch waist.

Stress of shotcrete presented approximate symmetric distribution shown in Figure 18. Stress in right side were slightly bigger than left. Stress value of shotcrete were between -0.55MPa and -5.32MPa, and all were compressive stress. Maximum stress was located in the middle of right wall.

Stress of lattice girder were lied between -8.9MPa and -14.8MPa, and all were compressive stress. Maximum stress was located in the right arch waist.

9. Conclusion
Based on Jiangshuiquan tunnel, parameters of horizontal layered rockmass were determined by rock test and in-situ experiment. Deformation characteristics of surrounding rock and structure stress were
analyzed by means of numerical simulation and in-situ test. The main conclusion were summarized as following.

1) As for horizontal layered rockmass, vertical elastic modulus was obviously smaller than lateral elastic modulus.

2) Vault settlement was the main deformation in horizontal layered rockmass. (3)Maximum tangential stress and minimum radial stress of surrounding rock were all emerged around the tunnel in layered rockmass.

3) During construction, rock block would fall down from arch shoulder and stratum delaminating would occur in vault rockmass.

4) Compared with other postions, pressure of surrounding rock, stress of shotcrete and lattice girder of the vault were relatively small. Field test indicated that support parameters were reasonable and support structure was safe.

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