Numerical investigation of anisotropic and time-dependent behaviors of tunnel invert structure in layered rock mass

Zhen Gao

Doctor, Key Laboratory for Urban Underground Engineering of Ministry of Education, Beijing Jiaotong University, Beijing, China. Email: 17115299@bjtu.edu.cn

ORCID: https://orcid.org/0000-0002-8833-6830

Xu Wu

Professor, Key Laboratory for Urban Underground Engineering of Ministry of Education, Beijing Jiaotong University, Beijing, China. Email: wu-xu@bjtu.edu.cn (Corresponding Author)

Ke Li

Master, Key Laboratory for Urban Underground Engineering of Ministry of Education, Beijing Jiaotong University, Beijing, China. Email: 20125891 @bjtu.edu.cn

Shuai Feng

Master, Key Laboratory for Urban Underground Engineering of Ministry of Education, Beijing Jiaotong University, Beijing, China. Email: 19121037 @bjtu.edu.cn

Abstract: In this paper, the bottom of the tunnel structure is uplifted with time under the condition of layered surrounding rock, and the influence of the change in slope angle on the bottom uplift is discussed. In addition, the finite difference method is used to simulate the limitation of the uplift deformation of the tunnel bottom structure by adjusting the rise span ratio of the inverted arch. The conclusions are as follows: (1) The “weak plane” in layered rock mass produces anisotropy of deformation. The creep speed of the surrounding rock is fast at the initial stage and then stabilizes after a certain period. (2) With different dip angles of the layered rock mass, the peak vertical displacement of the inverted arch filling layer is accordingly affected by the dip angle. (3) In engineering, the method of adjusting the rise span ratio to increase the depth of invert is usually applied to restrain the uplift deformation of invert structure. According to the numerical analysis results, with the increase in depth, the deformation inhibition capability does not become stronger. In addition, a similar situation occurs in the plastic zone of the filling layer. Thus, the rationality of deepening depth should be fully considered when adjusting the rise span ratio. This paper analyzes the numerical simulation of the tunnel substructure of a layered rock tunnel with time effect to provide a useful reference for the tunnel design under such surrounding rock conditions.
1. Introduction

In the process of transportation network construction in Southwest China, an increasing number of tunnels are constructed under layered surrounding rock conditions. Given the great differences between the weak plane of the bedding and structure of the matrix material, evident anisotropy is observed in the deformation and strength of a layered rock mass. Since the 1960s, as a result of the problem of layered rock deformation and stability in engineering, the term “anisotropy” has been gradually known in the field and widely studied\cite{1-4}. Layered rock mass generally contains a group of dominant structural planes, which are mostly “weak planes”; thus, the stability of engineering structures is largely controlled by the occurrence and characteristics of the dominant structural planes. During tunnel construction under a layered surrounding rock, the floor heave can only usually be exposed 3–6 months after the completion of the invert. However, given the orders of difference between the magnitude structural deformation monitoring index and the track deformation control index, this kind of invert structure heave accident at the initial stage of construction, is hard to detect. In addition, under the condition of soft rock with high in-situ stress, the creep of surrounding rock will lead to the uplifting deformation of the bottom structure of the tunnel, which will have a huge influence on the stress and deformation of the supporting structure and may eventually cause serious adverse social impacts.

Studies on the time effect characteristics of layered rock mass mainly focused on three aspects, namely, experiment, mechanical model, and numerical simulation. R. E. Thill et al.\cite{5} studied the variation law of longitudinal wave velocity with the direction of crack in rocks and proposed a method for determining the anisotropy of rock wave velocity; on the other hand, numerous scholars have also carried out a large number of experimental studies on anisotropic mechanical properties of layered rock mass. S. C. Hu et al.\cite{6} observed that the Young’s modulus and tensile strength of layered sandstone are evidently affected by confining pressure and loading angle. Griggs\cite{7} studied the creep characteristics of shale and sandstone and discovered that the creep deformation of rock occurs when the stress reaches 12.5%–80% of the maximum failure stress level. Li Yongsheng\cite{8} carried out indoor uniaxial compression test on rock with rigid testing machine and revealed that the creep of rocks generally has three stages: initial, constant-velocity, and accelerated creeps; as the first person who introduced the theory of rock rheology to China, Chen Zongji\cite{9} carried out rheological tests on the surrounding rock of adit and proposed the long-term strength of rock mass, determination method, and constitutive equation. The research on the time-dependent mechanical model of layered rock mass has also experienced a process from the creep constitutive study of intact rock to the creep study of rock with bedding characteristics. On the basis of Flac3D’s own cvisc elasto-plastic visco constitutive model, which can reflect rock creep, Huy et al.\cite{10} introduced a “weak plane” into the model and developed a layered rock creep constitutive model that can reflect the dominant joint plane. Based on the viscoelastic Burgers model, Li lielle\cite{11} derived the three-dimensional creep constitutive equation of transversely isotropic rock mass. The rheological phenomena of layered rock mass engineering are discontinuous, heterogeneous, nonlinear, and complicated loading and unloading and boundary conditions. Therefore, solving the problems of rock mass engineering by analytical methods is difficult. The numerical simulation method has a wide range of applicability. It can simulate the complex mechanical and structural characteristics of engineering rock mass and can be used conveniently to
analyze various boundary value problems and predict the rheological problems with time effect. The numerical simulation of time-varying effect of layered rock mass can be divided into two types: continuum mechanics model and discrete element model.

However, although the discrete element model can directly reflect the layered characteristics of rock mass, the computational efficiency of this method is lower than that of continuum mechanics method when the model is complex, and numerous calculation units are involved. Therefore, the time-varying effect of layered rock mass is commonly analyzed by embedding discontinuities, such as "weak plane," into the constitutive model of finite element. Yadav P[12] used the finite difference software Flac3D to analyze the deformation anisotropy of the mining chamber structure under the condition of layered compressive surrounding rock and the stress and deformation of different supporting structures under the rheological action. Lee C L et al.[13] developed the UBI/BUR model which can reflect the anisotropy and time-varying effect of layered rock mass by combining the joint and Burgers models. The model was used to simulate the excavation of actual tunnel engineering under the slate condition. The model parameters were calibrated by using the field monitoring data, and engineering analysis was carried out. This paper intended to analyze the time-dependent effect of the uplift deformation of tunnel substructures and the change in the invert rise span ratio under the condition of layered surrounding rock.

2. Calculation Principle

The finite difference software Flac3D was used to add a “weak plane” on the isotropic matrix. Meanwhile, based on different stress states, the binary power model with time effect was introduced to simulate the time effect of the layered rock mass. Figure 1 shows the schematic of the model.

![Viscoelastic plastic constitutive model of layered rock mass](image)

Figure 1. Viscoelastic plastic constitutive model of layered rock mass.

This model is suitable for simulating the anisotropic time-varying effect of layered rock mass. The available data are limited. Thus, the creep law model should not contain an excessive number of parameters. The creep strain rate of this model is obtained from Mises stress in accordance with the power law; the stress–strain relationship is as follows:

\[
\dot{\varepsilon}_c = A\bar{\sigma}^n
\]

(1)

where \(\dot{\varepsilon}_c\) is the creep rate, \(\bar{\sigma}\) is the Von–Mises stress, and \(n\) is the material creep parameter.

\[
\bar{\sigma} = \sqrt{3J_2}
\]

(2)

where \(J_2\) is the second invariant of the effective deviatoric-stress tensor.
The selection of creep parameters has been discussed in relevant literature\cite{14}. This paper used the values of $A$ and $n$ obtained from the field monitoring displacement inversion. During creep simulations, Itasca Consulting Group (2017a) assumed that the initial creep time step should be at least two to three orders of magnitude smaller than the critical one. In the meantime, the maximum value of the creep time step should less than or equal to the critical time step. According to analysis, the following equation was applied in the critical time step for the power-type creep model:

$$
\Delta t_{cr}^{\text{Max}} = \frac{\bar{\sigma}^{1-n}}{AG}
$$

where $\Delta t_{cr}^{\text{Max}}$ is the maximum time step, and $G$ is the shear modulus.

In this model, the creep behavior is driven by the deviatoric stress. In FLAC3D, the following procedure was used to achieve the aim of the power ubiquitous joint model. Compared with the isotropic creep model in creep calculation, the viscoelastic plastic change process of rock mass and “weak plane” were both considered in the calculation of this model. Thus, the time-varying effect of layered rock mass can be calculated and analyzed numerically.

3. Computational Model

The DK164+450-DK165+900 section of a tunnel under construction belongs to grade IV soft rock section. A tunnel floor heave deformation is estimated to occur in the tunnel, of which the buried depth is about 200 m, and the vertical geostress is 7.0 Mpa. The lithology of the formation is shale, argillaceous limestone intercalated with sandstone and carbonaceous shale. In addition, the groundwater is developed with seeping and linear water. Figure 2 shows the exposure of the layered rock mass on the working face of the construction site. In view of the surrounding rock conditions of deep buried soft rock, relevant units carried out research on deepening invert scheme.

![Figure 2. Layered rock face construction site.](image)

According to the site surrounding rock conditions, the article considered the dip angle of 20° of the slowly inclined laminated surrounding rock for numerical simulation analysis, such as the adjustment of the elevation arch vector-to-span ratio. The calculation model was a 100 m x 100 m plane strain model with a tunnel section $B \times H = 14.7$ m x 12.4 m, a hydrostatic stress field of 5.4 Mpa, full-section stress relief excavation, and timely application of primary support and second lining. In addition, the normal displacement of each boundary is constrained. The thickness of the primary support is 25 cm, and that of the secondary lining is 45 cm. Figure 3 displays the schematic of the model.
The elastic modulus of surrounding rock is determined on the basis of GSI surrounding rock classification system, which is widely used in foreign engineering circles to estimate the strength and deformation parameters of tunnels and caverns. The value of GSI is determined based on the geological survey data in the field. According to the analysis of the actual situation of large deformation in the field, the ratio of strength to stress was determined, and the uniaxial compressive strength, internal friction angle, and cohesion were obtained by combining the uniaxial compression experiment in the field.

The elastic modulus of concrete was determined in accordance with the railway design code, and the internal friction angle and cohesion of support were determined using the following formula.

\[ \sigma_c = \frac{2c \cdot \cos \phi}{1 - \sin \phi} \] (4)

Table 1 shows the material parameters of primary support, secondary lining, and invert filling layer in calculation.

| Material          | E/Gpa | ν  | C/Mpa | Φ/° |
|-------------------|-------|----|-------|-----|
| Primary support   | 23    | 0.3| 3.5   | 35  |
| Secondary lining  | 25    | 0.3| 4.4   | 35  |
| Filling layer     | 21    | 0.3| 2.6   | 35  |

Based on the deformation of the tunnel substructure measured in the field, combined with the engineering surrounding rock classification inversion, the parameters of layered surrounding rock were obtained (Table 2). For the selection of creep parameters, the relevant literature\cite{14} is referred to for the assignment.

| E/Gpa | ν  | C/Mpa | Φ/° | C’/Mpa | Φ’/° | A   | n  |
|-------|----|-------|-----|--------|------|-----|----|
| 1     | 0.25| 1.35  | 35  | 0.3    | 18   | 7e-30| 2.5|

3.1 Influence of weak plane inclination

Layered rock mass contains dominant planes with directional distribution, such as joints, fissures, faults, etc. Therefore, the failure mechanism and form of layered rock mass are different from those of other geological rock masses, and the anisotropic characteristics of strength and deformation of layered rock mass have a great influence on the deformation and failure of surrounding rocks. Usually, the deformation of surrounding rock is evidently asymmetric. First, considering the effect of creep time, the influence of dip angle of layered rock mass on the deformation of invert structure was
analyzed.

**Figure 4.** Schematic of measuring points for vertical deformation of invert structure.

For horizontal bedding and dip angles $30^\circ$ and $60^\circ$, the final vertical displacement and deformation of inverted arch filling layer after creeping for 400 days were obtained (Fig. 5):

**Figure 5.** Final vertical displacement of inverted arch filling layer after creeping for 400 days.

The power ubiquitous joint constitutive model was adopted, and the data in Tables 1 and 2 were selected for surrounding rock support parameters. Figure 6 shows the results of 400-day creep deformation of model rail surface elevation and plastic zone of surrounding rock structure.

**Figure 6.** Vertical displacement curve of track surface in layered rock mass.

Based on the creep analysis of 400 days for the ubiquitous joint model considering the time effect of layered rock mass, the following conclusions can be drawn from the calculation results in Figs. 5 and 6:

1. The vertical uplift displacement of the measuring points on the rail surface tends to converge in about 280 days, and the initial creep deformation increases rapidly with time. Under the condition of horizontal bedding, the final creep vertical displacement at the central ditch is the largest.

2. Changing the direction of the joint dip angle, the deformation of measuring points B and C that is symmetrical to the center of invert showed evident anisotropy, and the deformation of weak surface of layered surrounding rock produced a similar “bias” effect. The vertical displacement of measuring point C is larger than that of measuring point B on the whole trend.

3. With the increase in dip angle, the peak stable value of vertical displacement deviated along the direction of the vertical weak plane. Thus, the deformation anisotropy caused by the change in bedding dip angle should be considered in the process of tunnel design and construction.
3.2 Countermeasure analysis of tunnel bottom uplift project

Using the constitutive model and considering creep and layered rock mass at the same time, numerical simulation was carried out on the common countermeasures of tunnel invert uplift in engineering, such as changing the ratio of rise to span of invert and deepening of the invert. Figure 7 shows the schematic of invert deepening. Based on the vertical deformation of tunnel bottom and plastic zone of filling layer, the rationality of tunnel bottom deformation in the layered rock mass was studied.

Figure 7. Schematic of deepening invert.

Flac3D was used to calculate the time-varying vertical displacement and deformation of three points A, B, and C on the surface of the filling layer and the plastic zone of the substructure at the design section and different invert rise span ratios. The calculation results are shown in Figs. 8 and 9.

Figure 8. Time-dependent vertical displacement of points A, B, and C on the rail surface with different rise span ratio.
Figure 9. Change diagram of plastic zone after adjusting the rise span ratio.

Given the results shown Figs. 8 and 9, we obtained the following conclusions:

1. When the rise span ratio of the invert was adjusted to deepen the depth of the invert, the vertical displacement of the rail surface on the filling layer decreased and stabilized when it reached a certain depth, which indicates that adjusting the rise span ratio of the invert to deepen the invert can inhibit the uplift deformation of the tunnel substructure caused by the creep of the surrounding rock. In addition, the findings show that the deeper the invert is, the more effective it is.

2. Under the original design condition, the vertical displacement of point a on the rail surface of the filling layer increased by about 14 mm, and the vertical displacement of point a was about 8.7 mm when the invert was deepened by 120 cm. The vertical displacement of points B and C on the surface of the filling layer was stable when the invert was deepened by 80 cm.

3. With the increase in the invert depth, the plastic area of the filling layer decreased, and the filling layer was filled into a plastic zone dominated by material tensile failure. When the invert was deepened to 120 cm, the filling layer showed no tensile failure. From the point of view of the change in plastic zone, when the invert is deepened to a certain depth, the material of filling layer will not be damaged any more.

4. Conclusion and Prospect

Considering the creep time effect of the layered surrounding rock, the following conclusions can be obtained for the numerical simulation of tunnel substructure:

1. The vertical displacements at the center of the elevated arch were larger in the range of 0°–30° of laminar inclination, whereas the peak vertical displacements of the infill layers produced significant anisotropy as the inclination angle changes.

2. Changing the rise span ratio of the invert structure and increasing the depth of the invert are a common method to limit the uplift deformation of the tunnel substructure, and the reasonable depth of the invert should be fully considered in the design.

3. When using finite difference method to analyzed the layered surrounding rock, considering the thickness of the surrounding rock, joint stiffness, joint size, and other problems is impossible. Thus, the equivalent method or discrete element method should be considered for in-depth analysis.

Reference

[1] LEKHNIITSKII S G. Theory of Elasticity of an anisotropic elastic body [M]. San Franciesco: Holden-Daty Inc., 1963: 58–73.

[2] RABINOVICH N R. The state of stress around an arbitrarily oriented mine working driven in an anisotropic rock mass[J]. Soviet Mining Science, 1976,11(6): 622–626.

[3] SUN Guangzhong. The rock mass structure mechanics[M]. Beijing: Science Press, 1988: 204–221.
[4] XIAN X and TAN X. 1989 The failure mechanism of layered rock mass Chongqing. Chongqing.

[5] THILL R E, BUR T R and STECKLEY R C 1973 Velocity anisotropy in dry and saturated rock spheres and its relation to rock fabric. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts. 10(6): 535–57.

[6] HU S C, TAN Y L, ZHOU H et al 2017 Impact of Bedding Planes on Mechanical Properties of Sandstone. Rock Mechanics and Rock Engineering. 50(8): 2243–51.

[7] GRIGGS D T 1939 Creep of rock. Journal of Geology. 47: 225-51.

[8] Li Y 1995 Four types of rocks under uniaxial compression Experimental study of creep and relaxation. Chinese Journal of Rock Mechanics and Engineering. 14(1): 39—47.

[9] TAN T K, LI K 1981 Relaxation and creep properties of thin interbedded clayey seams and their fundamental role in the stability of dams [C]//Proceedings of the International Symposium on Weak Rock. Tokyo. International Society for Rock Mechanics and Rock Engineering  369-74.

[10] Huy, Tran, Manh, et al 2015 Anisotropic Time-Dependent Modeling of Tunnel Excavation in Squeezing Ground. Rock Mechanics & Rock Engineering.

[11] Li L 2020 A creep constitutive model for transversely isotropic rocks. Rock and Soil Mechanics. 41(9):2922-30, 2942.

[12] Yadav P 2018 Numerical investigation of anisotropic and time-dependent behaviours of foliated rock mass.

[13] Lee C L, Shou K J, Chen S S, et al 2019 Numerical analysis of tunnelling in slates with anisotropic time-dependent behaviour. Tunnelling & Underground Space Technology. 84(FEB.):281-94.

[14] Tsenn M C, Carter N L 1987 Upper limits of power law creep of rocks. 136(1):1-26.