Research Article

Li Guo* and Yi He

Optimal control and nonlinear numerical simulation analysis of tunnel rock deformation parameters

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Abstract: In order to study the influence of nonlinear numerical simulation on the optimal control of the tunnel rock deformation parameters, the author proposes a numerical simulation study of the deformation characteristics of the layered rock tunnel, and determines the calculation model according to the thickness of the rock mass. The estimated thicknesses of the dolomite limestone surrounding the tunnel are 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 m. Select the vertical displacement to analyze as a result of the calculation. In order to study the influence of the structural slope on the tunnel stability, the thickness of the rock layer was 0.6 m, and the structural slopes of 5°, 15°, 30°, 45°, 60°, 75°, and 85° were used for simulation calculations. During on-site construction, focus on monitoring the tunnel section deformation before the construction of the secondary lining. Every 10–20 m and at the change of the surrounding rock, the observation section of the surrounding convergence and vault settlement shall be arranged, according to the observed deformation, the peripheral displacement rate and the vault subsidence rate are calculated. The results show that the vertical displacement of the top of the tunnel is generally in a “V” shape, that is, the maximum settlement in the tunnel; when the layer thickness is 0.3 m, the maximum vertical displacement of the rock layer is 7.2 mm, and the total settlement in the lining support tunnel is 8.23 mm. When the layer thickness is 0.9 m, the vertical displacement of the rock layer is 5.14 mm, and the total settlement in the lining support tunnel is 5.22 mm. When the layer thickness is from 0.9 to 0.3 m, the maximum vertical displacement of the rock layer increases by 140%, and the settlement at the vault increases by 158%. The focus of tunnel support at this time is the two sides of the lining structure and the vault with large vertical settlement. For the YK51 + 032 section, the phenomenon of first decreasing and then increasing is due to the sudden mud on the surrounding YK51 + 040, which causes the short-term deformation to increase. Only the ZK49 + 356 sections at the entrance of the spider has very good deformation due to the thin overlying stratum, and other sections are similar, which shows the reliability of the calculation results.

Keywords: tunnel, rock deformation, nonlinear numerical simulation, layered rock mass, dip angle

1 Introduction

At this stage, the deformation control of tunnel construction is still unsatisfactory, especially the deformation problems of tunnels with high ground stress and weak surrounding rock are still relatively prominent, it is manifested as rapid deformation, large deformation, and long-lasting deformation, which is easy to cause the support to be dismantled and replaced due to intrusion or damage, and the construction safety risk is high. It often leads to delays in construction period and increased investment, which brings great risks and challenges to tunnel survey, design, construction, and management [1]. The existing supporting technology is summarized and analyzed, construct a tunnel support system based on active deformation control, and study its support mechanism and key support technologies. In order to ensure the safe construction of railway tunnels, it is of certain significance to innovate the theory and method of railway tunnel support. Figure 1 shows the solution of the online monitoring system for tunnel deformation. To solve the deformation problem, scientists have used methods such as field experiments, mathematical simulations, and theoretical analysis [2].

* Corresponding author: Li Guo, School of Civil Engineering, Luoyang Institute of Science and Technology, Luoyang, Henan 471023, China, e-mail: guoli8@126.com

Yi He: School of Civil Engineering, Luoyang Institute of Science and Technology, Luoyang, Henan 471023, China, e-mail: yihe727@163.com

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At present, there are certain deficiencies in the active control and support of surrounding rock deformation of railway tunnels in China, which are mainly manifested as follows: railway tunnel support is generally a passive support system; at present, railway tunnel support generally emphasizes the deformation control of passive support members such as steel frames, and the support construction cannot effectively strengthen the surrounding rock. The support system based on passive support is suitable for tunnels with good surrounding rock, but under difficult conditions such as poor self-supporting capacity of surrounding rock and high in situ stress, it is difficult to control deformation only by passive support; the supporting structure is easily deformed and damaged, and accidents such as tunnel collapse occur [3]. The concept of active support is still not unified, in the construction of railway tunnels for many years, the importance of active deformation control has been generally realized, and it is emphasized that active support should be used to prevent active deformation, the bearing capacity of the surrounding rock is fully utilized to control the deformation, and the supporting measures such as pre-stressed bolts (cables) and grouting reinforcement of the stratum have been extensively studied and applied. However, at present, there is no unified understanding of the support concept, application conditions, and scope of application of active deformation control [4]. The key technologies of the active support system need further innovation, the effect of active support depends on high-performance support materials; at present, the mechanical properties of support materials or components are generally low, if the support force performance cannot be fully exerted, high-performance shotcrete material technology, new anchoring material technology, and non-destructive testing technology for initial support construction quality should be studied, achieve rapid construction, and timely effect of tunnel support [5].

2 Literature review

In terms of weather and hydrology, weather and hydrology conditions are important factors in causing tunnel collapse. In response to this research problem, Nedelescu et al. proposed the concept of active control deformation. Bolt (cable) support and surrounding rock grouting are considered to be active support, while steel frame support, shotcrete support, and secondary lining are passive support [6]. According to the mechanism of tunnel support, Pal divided the types of tunnel support into two categories, namely active support and passive support. Passive support is passively applied to the surrounding rock; it is a support system that has relatively little effect on controlling the mechanical properties of the surrounding rock [7]. Li et al. put forward the mechanical support theory of soft rock engineering, systematically introduced the definition, basic properties, and continuity generalization of soft surrounding rock, and proposed the determination of deformation mechanics mechanism, support load determination, and support design method [8]. Luo et al. proposed
the release-constrained balance method, the deformation of surrounding rock is controlled from two aspects of releasing in situ stress and optimizing support. The main measures for stress release are reserved deformation and advanced pilot holes. Optimized support includes measures such as strengthening support, strengthening locking feet, timely closure, and dynamic reinforcement [9]. Wu et al. proposed the classification of weak surrounding rock, tunnel section, and span classification, and established a tunnel structure system with weak surrounding rock [10]. Li et al. proposed a stability classification method for large-section tunnels, and based on the face wedge failure mode and limit equilibrium theory, the advanced support design method of the tunnel full-section method construction face is proposed, which provides a theoretical guarantee for the tunnel full-section method construction face [11]. Liu et al., through their research on micro- and macro-non-photorealistic rendering (NPR) materials and structures, as well as their application in practical engineering, for the first time in the field of rock mechanics, the scientific problem of the concept and mechanical behavior of NPR support structure was proposed, and on this basis, it is proposed that “no matter what kind of engineering geological structure the rock mass has, after the NPR support is embedded, it will have the same constitutive relationship as the NPR bolt/cable” [12]. Wu et al. studied the structure, constitutive model, and energy absorption characteristics of NPR anchor cables, and used Flac3D to establish NPR anchor cable constitutive numerical simulation experiments, the actual deformation characteristics of the NPR cable were fitted [13]. Zhang et al. used Flac3D to simulate and analyze deep tunnels and their supports [14]. Matyushkin proposed a variety of methods to simulate the mechanical behavior of surrounding rock and bolts, which promoted the application of Flac3D in tunnel engineering [15]. On the basis of the existing research, the author proposes nonlinear numerical simulation analysis to optimize the deformation parameters of the tunnel rock layer, and uses the ANSYS finite element software to analyze the stress and deformation characteristics of the surrounding rock and foundation after the tunnel layer is excavated. ANSYS software is a large-scale general-purpose finite element analysis (FEA) software developed by ANSYS Company, USA. It is the fastest growing computer-aided engineering software in the world. It can interface with most computer-aided design software. Realize data sharing and exchange, such as Creo, NASTRAN, Algor, I-DEAS, AutoCAD, etc. It is a large-scale general-purpose FEA software that integrates the analysis of structure, fluid, electric field, magnetic field, and sound field. It has a wide range of applications in nuclear industry, railway, petrochemical, aerospace, machinery manufacturing, energy, automobile transportation, defense industry, electronics, civil engineering, shipbuilding, biomedicine, light industry, geology and mining, water conservancy, household appliances, etc. With powerful functions and simple and convenient operation, ANSYS has become the most popular FEA software in the world, ranking first in FEA evaluations over the years. There is obvious inhomogeneity because the displacement on one side of the rock layer slope is smaller than that on the other side. Therefore, the roughness first increases and then decreases. The slope angle increases most obviously at 45°, and gradually stabilizes when it is greater than 60°; the displacement of the arch and wall is less affected by the change of the slope. The design and construction of layered rock tunnel support should avoid accidents caused by excessive deformation and uneven deformation of the tunnel.

3 Methods

3.1 Computational model

Since only the influence of surrounding rock changes was studied, a two-dimensional plane model was established. In order to reduce the adverse effect of boundary effects, the final size of the model was determined to be 100 m × 100 m. The thickness of the weak interlayer between rock layers is calculated as 2 cm. The origin of the coordinates is 10 m directly below the tunnel arch bottom, and the rest of the depth is converted into the pressure load of the corresponding layer thickness. The pressure load applied in the dip model is the self-weight load of the rock and soil in each half-time. The lower boundary fixes the horizontal and vertical displacement, and the left and right only constrain the horizontal displacement [16]. The mechanized construction method of tunnel drilling and blasting method is based on high-efficiency large-scale machinery in the whole process, and is a technical method to solve the construction problems of safety, high quality, high efficiency, and economy of the complex mountainous Changshanling tunnel. All geological construction technology, face stability evaluation method, face advance active support technology, “quantitative” precise design technology of face advance support, low pre-stressed bolt active support technology, and early high-intensity injection The key technologies of tunnel drilling and blasting mechanized construction design with the core of concrete active support technology, initial support rapid ring-forming and sealing technology, and surrounding rock deformation pressure calculation method provide technical support for the popularization and application of tunnel drilling and blasting mechanized construction method.
3.2 Calculation parameters

The physical and non-physical compositions of the selected materials are shown in Table 1, using the normalized calculations of the planar and D–P models.

3.3 Construction of NPR anchor cable constitutive model

The disadvantage of ordinary anchor cable relative to NPR anchor cable is that its deformation is small, under the condition of large deformation or impact of surrounding rock, the anchor cable is damaged due to excessive deformation [17]. NPR anchor cable can not only adapt to large deformation surrounding rock, but also provide effective high constant resistance. It is necessary to redefine the anchor cable element (geometry, material parameters, and anchoring agent properties) using Fish language in Flac3D, the NPR anchor cable is an elastic–plastic body, its characteristics are described by a one-dimensional constitutive model, and its axial stiffness $K$ can be expressed as:

$$ K = \frac{AE}{L}. $$

In the above formula, $A$ is the reinforcement cross-sectional area ($m^2$), $E$ is the elastic modulus (GPa), and $L$ is the member length (m).

In Flac3D, the tensile yield strength $F_t$ and compressive strength $F_c$ of the anchor cable can be specified, and these two limits cannot be exceeded in the application of the constitutive model [18]. The parameters that govern the performance of NPR cables are tensile strength and tightening parameters, PR (normal) cables reaching their tensile strength limit due to pulling, or failure of the fasteners when installing NPR anchors. The strength of the anchor cable unit and the tightening agent is adjusted to be greater than the tensile strength of the anchor cable, which is rigidly connected with the surrounding rock, and the free end of the anchor cable is also adjusted to be rigidly connected with its surroundings, imitating stones, and shelves. By adjusting the high deformation of the anchor cable when a constant resistance value is reached, it is possible to lengthen the anchor cable, filter the distance between the free end and the anchor end using the built-in Fish language, and control the anchor cable anchor force. When the anchor cable and the deformation value reach a predetermined value, the anchor cable unit is loosened [19].

4 Results and analysis

4.1 Analysis of the influence of the thickness of the layered rock mass on the tunnel

When studying the effect of layered rock mass on the tunnel stability, the thickness of the dolomite limestone around, assuming that the dip angles of the stratigraphic structure were 0, 0.5, 0.6, 0.7, 0.8, and 0.9 m. In the calculation results, select vertical displacement for analysis. When the inclination of the rock formation is zero, layered rock mass can be regarded as a flexural member bearing uniformly distributed loads, no matter how the layer thickness changes, the vault is the part where the vertical displacement of the tunnel changes the most [20]. Therefore, when the layered jointed rock layer is horizontal, the key point of lining support should be the dome position during tunnel excavation construction [21]. Select the vertical displacement of rock layers with different thicknesses and lining support arch tops with a horizontal length of 15 m directly above the vault, and draw the vertical settlement curves of the rock layers and the cumulative value of vault settlement at different layer thicknesses, as shown in Figures 2 and 3.

In Figure 2, the origin of the abscissa in the tunnel, the left side of the tunnel is positive and the right side is negative, the result of longitudinal displacement ignores the mode settlement caused by self-weight load. It can be seen that the vertical displacement of the top of the
4.2 Analysis of the influence of the inclination angle of the rock stratum structure on the tunnel

Since 0.6 m is the critical layer thickness of the deformation speed, the rock layer thickness of 0.6 m is selected when studying the plane dip angle characteristics of the tunnel stability, and the standard plane dip angles are 5°, 15°, 30°, 45°, 60°, 75°, and 85° for simulation calculation. The displacement on one side of the rock stratum is smaller than that on the other side. The asymmetry of the displacement cloud map first increases and then decreases, when the rock formation dip angle is close to 90°, this asymmetry will disappear. The deformation point with the largest settlement displacement for the lining structure is always the vault of the tunnel. It can be concluded that the dome position is the key point of lining support when the tunnel layer is excavated [28].

According to the distribution characteristics of the vertical displacement of the lining, six main points of the rock and lining around the tunnel are selected: the vertical displacement of the main point obtained from the tunnel, and the corner. The bottoms of the left and right reverse arches and basement arches are shown in Figures 4 and 5.

From Figure 4, the vertical displacement and settlement of key points A (vault top) and F (vault bottom) decrease with the gradual increase of rock inclination from 5° to 85°, especially when the inclination angle of the rock formation is from 5° to 45°, the variation of the vertical displacement and settlement is large [28]. Moreover, with the increase of the inclination angle of the rock stratum is generally V-shaped, that is, the maximum settlement in the tunnel [22]. The perpendicularity of the lining support frame is 5.22 mm; from 0.9 to 0.3 m, the maximum vertical displacement of the formation increased by 140%, and the settlement in the tunnel increased by 158%. It is clear that the stability of the tunnel is greatly affected by the thickness of the rock layers. As the thickness of the rock increases, the deformation of the upper part of the tunnel gradually decreases. If the thickness is 0.4–0.6 m, the vertical displacement decreases rapidly, but if the thickness is greater than 0.6 m, the displacement does not change much [23–27].
structure, the difference in displacement and settlement of key points at the same height first increases and then decreases, such as points B and C and points D and E. Since the inclination of the rock formation increases from 5° to 45°. The difference between the settlements on both sides increases, and the displacement of the rock mass on both sides increases gradually asymmetrically. As a result, the relative sliding tendency between the rock layers on the left and right sides will also increase. Also, it may even lead to the damage of the lining structures. The inclination angle $\theta$ of the rock structure plane increases gradually from 45° to 85°. The difference between the settlements on both sides decreases, and the displacement of the rock mass on both sides decreases gradually asymmetrically.

From Figure 5, it can also be determined that when the depth is constant and the inclination angle is gradually increased, due to the balance of the left and right sides of the lining, the dislocation of the balls causes friction. Therefore, it was decided to excavate the tunnel at an inclined position, with the support core on both sides of the structural lining and the vault with the larger vertical settlement.

### 4.3 On-site monitoring and analysis

During on-site construction, focus on monitoring the tunnel section deformation before the construction of the secondary lining. Peripheral convergence and vault settlement detection sections are set every 10–20 m, and the door body value is calculated according to the visible deformation. Due to space limitations, the peripheral convergence and the distribution range of the vault displacement rate for one observation period of some sections are listed, as shown in Tables 2 and 3.

#### 4.4 Discussion

It can be seen from Tables 2 and 3 that, except for the YK51 + 032 sections, the deformation rate of each section at the inlet and outlet gradually decreases with time. For the YK51 + 032 section, the phenomenon of first decreasing and then increasing is due to the sudden mud on the surrounding YK51 + 040, which causes the short-term deformation to increase. The layer thickness varies from 0.3 to 0.6 m, comparing the simulation results of tunnel vault settlement in Table 3 and Figures 2–5, only the ZK49 + 356 section at the entrance of the left line is greatly deformed due to the thin overlying strata, and other sections are relatively consistent, indicating the reliability of the calculation results.

### Table 2: The distribution range of the convergence displacement rate of the BC survey line in some sections

| Station      | (1.5)  | (0.2,1] | ≤0.2 |
|--------------|--------|---------|------|
| ZK49 + 356   | 8.59–8.26 | 8.26–8.3 | 8.3–10.4 |
| ZK49 + 380   | 9.5–9.1 | 9.11–9.17 | 9.17–10.28 |
| YK49 + 330   | 8.14–8.18 | 8.18–8.23 | 8.23–10.5 |
| YK49 + 340   | 8.19–8.26 | 8.26–8.29 | 8.29–10.1 |
| ZK51 + 020   | 8.19–8.3 | 8.3–9.29 | 9.29–10.1 |
| ZK51 + 040   | 8.09–8.17 | 8.17–8.29 | 8.19–10.3 |
| YK51 + 032   | 8.17–8.24 | 8.24–8.3 | 8.3–10.13 |
| YK51 + 025   | 9.1–9.21 | 9.21–9.24 | 9.24–10.13 |

### Table 3: Distribution range of displacement rate of partial section vault

| Station      | (1.5)  | (0.2,1] | ≤0.2 |
|--------------|--------|---------|------|
| ZK49 + 356   | 8.59–8.26 | 8.26–8.3 | 8.3–10.4 |
| ZK49 + 380   | 9.5–9.1 | 9.11–9.17 | 9.17–10.28 |
| YK49 + 330   | 8.14–8.18 | 8.18–8.23 | 8.23–10.5 |
| YK49 + 340   | 8.19–8.26 | 8.26–8.29 | 8.29–10.1 |
| ZK51 + 020   | 8.19–8.3 | 8.3–9.29 | 9.29–10.1 |
| ZK51 + 040   | 8.09–8.17 | 8.17–8.29 | 8.19–10.3 |
| YK51 + 032   | 8.17–8.24 | 8.24–8.3 | 8.3–10.13 |
| YK51 + 025   | 9.1–9.21 | 9.21–9.24 | 9.24–10.13 |
5 Conclusion

The optimal monitoring and nonlinear numerical simulation analysis of tunnel rock deformation parameters are proposed, and the surrounding rock, basement stress, and deformation characteristics after excavation of layered dolomite limestone are analyzed by using ANSYS end element software. The vertical movement of the opening is divided into a “V” shape, and the maximum vertical rotation occurs on the ground. As the thickness of the stone layer increases, the maximum vertical displacement decreases with increasing rock thickness. The thickness of the rock formation is greater than 0.6 m. This is the defined critical thickness; it is clear that the displacement of the rock mass and lining around the slope tunnel will be non-uniform. The displacement of one side of the rock layer is smaller than that of the other side, and the unevenness increases first with the increase of the drop and decreases later. The angle is most obvious when the slope is 45°, and gradually stabilizes when the slope is greater than 60°. The planning and construction of layered rock tunnel support should avoid accidents caused by excessive deformation and uneven deformation of the tunnel. In the future, it is necessary to analyze several factors causing large deformation of surrounding rock, study other factors and their relationship, disaster mechanism, quantitative evaluation index of each factor, and standard for determining the stability of surrounding rock. Further improvement is required. Further research on the creep and strength development law of loose rock in high pressure environment, the rheological mechanism of loose surrounding rock tunnel, and the design structure of surrounding rock is of great significance for longevity.

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