Study on the Reserved Deformation of Large Section Soft Rock Highway Tunnel Based on Monitoring Measurement

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Abstract. Large section soft rock highway tunnel has the construction of large highway engineering. In the process of excavation, large section highway tunnel is prone to large deformation with the poor stability of surrounding rock and complex stress. We determined the deformation of the large section soft rock highway tunnel. Through a comprehensive code comparison, based on the scene early monitoring, the paper guaranteed the quality of the reserved deformation rate of the tunnel, which was optimized and verified in engineering practice based on monitoring and measurement in a certain quality assurance rate. The reserved deformation of rock mass was feasible, fully reflecting the characteristics of information construction methods. It provides reference for identifying similar construction of soft rock highway tunnel with large cross section deformation.

1. Introduction

Highway construction has entered a new period with the development of economic construction and continued investment in national infrastructure construction combined with the national strategy to the Belt and Road, transportation network in the southwest hub will be gradually formed. In the process of highway construction in the southwest mountain area, tunnel is widely used to ensure the safety of operation, avoid damage to the ecological environment, and shorten the mileage and so on. So far, in the world of highway tunnel size and ownership, China has jumped to the first [1]. Chinese railway tunnel re-entered a period of rapid development with the Belt and Road national strategic and has built a large number of railway tunnels, such as Wushaoling tunnel. However, shallow depth and poor conditions of surrounding rock is the most commonly encountered situation in the construction of tunnel project.

Among the many problems encountered in the actual construction of the tunnel, the most difficult problem is the large deformation caused by the excavation of the tunnel in the soft surrounding rock. Large deformation of the tunnel is easy to cause instability of surrounding rock, and many problems encountered in the process of excavation will lead to design changes. Therefore, it affects the progress of the construction so that the final investment cannot be estimated [2].

The reasons of large deformation of surrounding rock are complex and varied, because of the high degree of weathering and crushing of surrounding rock. There are tectonic stress and high ground stress caused by strata. Support structure cracking is caused by the deformation and collapse of the...
surrounding rock. These are accidents and situations prone to occur in the tunnel excavation under the condition of weak surrounding rock. At present, the prevention and control of large deformation about soft surrounding rock has become a hot spot in the research of underground engineering and geotechnical engineering [3]. It sets aside a reasonable amount of deformation in the management of tunnel surrounding rock large deformation problems in addition to the complex supporting measures. Meanwhile, it is a kind method allowing the surrounding rock release the proper deformation and stress to ensure the safety of the two lining of the reserve, which is more economical and reasonable. The surrounding rock is made to produce a reasonable amount of deformation in the process of tunnel excavation, compared with the complicated treatment of large deformation. Furthermore, for the determination of reserve in weak rock tunnel deformation, it is still in the engineering analogy method to be realized, lack of a set of effective theories and methods. This paper is proposed in this project background, expecting to determine the soft deformation of large deformation of surrounding rock tunnel deformation in a practical way.

2. Mechanism analysis of large deformation of tunnel

2.1. Large Deformation Law of Weak Surrounding Rock

The deformation of surrounding rock is the deformation of the complex geological body around the tunnel, with the complexity of its deformation mainly existed in the following aspects [4,5]:

1. The complexity of the material composition: rock and soil material composition is complex and diverse, e.g., hard granite and quartz. There is weak talc, gypsum, calcite and so on.

2. Structural discontinuities: Rock mass is also prone to occurring in the surrounding rock structure discontinuity fault, joint, bedding, unconformity and other geological structures.

3. The uneven distribution of material: it is uneven for the distribution of rock mass density in the area of the tunnel; the soft rock interaction layer and the soil rock mixture have occurred.

4. The material composition of the surrounding rock by external conditions is caused by changes in activity, such as mudstone. Phyllite by the influx of groundwater is easy to soften, with montmorillonite water expansion.

2.2. Large deformation mechanism in weak rock

From the above analysis results, the main deformation characteristics of soft rock tunnel can be summarized as follows: (1) large deformation; (2) high deformation rate; (3) extrusion deformation occurred in the face due to rock stress release; (4) support damaged in various forms under large deformation load.

In the mechanism analysis and research on the large deformation tunnel of weak surrounding rock, the Rubinets formula is introduced, and the detailed expression is shown as following Formula (1).

\[
R_p = R_{p0} + R_{p0} f(\theta) = R_0 \left[ \frac{P_0 (1 + \lambda) + 2C \cot \phi (1 - \sin \phi)}{2P + 2C \cot \phi} \right]^{1 - \frac{\sin \phi}{\tan \phi}} \times \left[ 1 + \frac{P_0 (1 - \lambda)(1 - \sin \phi) \cos 2\theta}{P_0 (1 - \lambda) + 2C \cot \phi \sin \phi} \right]
\]

Where \( R_p \) is the plastic zone radius of tunnel; \( R_{p0} \) is the radius of axisymmetric plastic zone; \( R_{p0}(\theta) \) is the radius of the plastic zone associated with \( \theta \); \( P_0 \) is the vertical initial stress; \( \lambda \) is the horizontal initial stress coefficient; \( C \) is the cohesion stress; \( \phi \) is the internal friction angle; \( P \) is the support resistance; \( R_0 \) is the tunnel radius.

Formula (1) basic ideas can be summarized as the following Fig.1, the general situation of the circular tunnel is divided into 1 and 2 of the superposition.
Total working condition

Condition 1 (axisymmetric)

Condition 2 (related to $\theta$)

**Figure. 1** Elastic-plastic analysis of circular tunnel.

Corresponding general circular tunnel elastic-plastic displacement can be expressed by Formula (2).

$$\mu = \frac{1}{4Gh} \left[ R_0^2 + (1 + \lambda)R_{po}(\theta) \right] \left\{ \sin \phi \left[ (1 + \lambda)P + 2C \cot \phi \right] \left[ 1 - \left( \frac{1 - \lambda \sin \phi}{R_0 \left( 1 - \sin \phi \right)} \right) \right\}$$

(2)

Where $\mu$ is the peripheral displacement; $G$ is the shear modulus; $E$ and $\mu$ are elastic modulus and poisson's ratio, respectively; $R_{P0}$ and $f(\theta)$ can be expressed as following Formula (3) and (4).

$$R_{P0} = R_0 \left\{ \frac{P \left( 1 + \lambda \right) + 2C \cot \phi}{2(P + C \cot \phi)} \right\}$$

(3)

$$f(\theta) = \frac{P \left( 1 - \lambda \right) (1 - \sin \phi) \cos 2\theta}{P^2 \left( 1 - \lambda \right) + 2C \cot \phi \sin \phi}$$

(4)

According to Formula (1) and (2), the deformation of tunnel construction is influenced by the physical and mechanical properties of surrounding rock, the original stress condition, the size of tunnel...
section, the way of support and so on. Where, the horizontal side pressure coefficient is important to
the distribution shape of the plastic zone, and then the deformation of the tunnel has a corresponding
effect. Generally, in the numerical simulation analysis, the coefficient of lateral pressure is often taken
as 1, then Formula (1) and (2) are transformed into:

\[ \begin{align*}
R_p &= R_0 \left[ \frac{\left( P_0 + C \cot \phi \right) \left( 1 - \sin \phi \right)}{P + C \cot \phi} \right]^{\frac{1 - \sin \phi}{2 \sin \phi}} \\
\mu &= \frac{R_p^2}{2GR_0} (P_0 + C \cot \phi) \sin \phi
\end{align*} \] 

\tag{5} \tag{6}

According to Formula (6), it can be concluded that the deformation of tunnel surrounding rock is
proportional to the square of the radius of plastic zone, so the plastic zone in the process of tunnel
construction is bound to exist at the same time with large deformation. The magnitude of the strength
index of the surrounding rock, the magnitude of the in-situ stress and the resistance provided by the
supporting structure determine the appearance of the large-scale plastic zone as Formula (5). In a
certain stress condition, strength index of soft rock is relatively low, easily leading to a large range of
plastic zone production. If without timely support or support measures are not up to the failure, it will
inevitably lead to large deformation. Formula (6) shows the deformation of tunnel diameter, and shear
modulus G is inversely proportional. Because of the relatively low shear modulus of the weak
surrounding rock, the probability of large deformation in the corresponding tunnel construction
process increased significantly. In addition, the tunnel excavation section size also has a significant
impact on the construction deformation.

In summary, the internal factors and external factors are the main factors that lead to large
defor- mation in the soft rock tunnel construction process. The physical and mechanical properties of
high ground stress and weak surrounding rock are its internal factors; excavation section size and
support measure the improper external cause.

3. Reserve tunnel deformation and its influencing factors

3.1. Implication of reserved deformation in tunnel and its significance

Four parts of the tunnel section are composed of two thickness of the lining, the amount of the
reserved deformation, the thickness of the initial support and the size of the section excavation.
Reserved deformation is set between the primary support and the secondary lining, for the tunnel and
the initial support deformation to reserve space size. It is economically reasonable and effective for
how much deformation is reserved for large deformation tunnels. This is very important in engineering
practice. As we all know, the amount of reserved deformation is too large, and it is equivalent to the
tunnel super dig, which will cause unnecessary economic waste. According to statistics, the tunnel
over-dug 1 cubic meter per meter of rock, the relative increase in the cost of excavation is relatively
small, causing the 1 cubic meter of concrete backfill and support engineering cost is very large.
Reserved deformation is too small; however, it may cause frequent change arch tunnel, seriously
affecting the construction progress and restricting the construction cost and time limit for a project [6].
So for soft rock large deformation tunnel, we researched the deformation law and the cause of large
deforation factors, with the determination of the reasonable reserved large deformation tunnel
deforation, guidance of later similar engineering design and construction, reduction of the
construction cost, and improvement of the quality of construction. It has important research
significance.

Aiming at the problem of large deformation of surrounding rock, on the one hand it is to strengthen
the construction quality, slow down construction progress, and improve the supporting strength; on the
other hand, it controls the reserved deformation size to meet the deformation of surrounding rock.
Aiming at the large deformation tunnel of weak surrounding rock mass, Construction cost, quality and time limit control are important factors to determine the reasonable reserved deformation. The reasonable deformation is to avoid the occurrence of over break or intrusive tunnel.

3.2. Influence factors of the value of reserved deformation

In the tunnel pre-design, one of the main design content is that of the tunnel excavation contour, with the unknown design of tunnel inner contour on the outline of the excavation face. The full consideration is allowed for deformation of surrounding rock deformation, with the size of the tunnel excavation determined by setting the amount of deformation to meet the deformation of the surrounding rock. It should be pointed out here that the allowable deformation amount is a range value, not necessarily equal to the reserved deformation value. The reserved deformation amount is directly related to the final deformation amount, and its influence factor is also the same. In determining the allowable amount of deformation, it needs to take into account the various factors that affect it as follows:

(1) The physical and mechanical properties of rock, especially the influence of the creep deformation characteristics, are the surrounding rocks of the Zhonghecun tunnel, which are mainly mudstone. In the process of excavation, the surrounding rock has a continuous deformation with time, and the final deformation is relatively large.

(2) The influence of the original earth stress: If the tunnel is through the location of the existence of a structure, such as the fault zone, it is prone to large deformation.

(3) The influence of the construction method: By step method the final deformation is larger than the full section excavation deformation. In the selection of construction and excavation methods, to combine with the situation of surrounding rock selection and soft surrounding rock conditions, it certainly cannot choose the full section excavation.

(4) The influence of the excavation speed of the construction process. The faster construction speed leads to the smaller final deformation; the slower construction speed, and the larger final deformation.

(5) The influence of the type of support, that is, in the actual construction process, to advance the support. The lead in the final deformation is performed for about 4 times. It can also make the surrounding rock shorten the convergence time.

(6) The influence of tunnel depth: Under the condition of the same surrounding rock, the depth of the tunnel is usually deeper, and the final displacement is larger.

(7) The influence of tunnel section: The bigger tunnel section size results in the larger final deformation.

4. Determination of reserved deformation in tunnel

Lanchuan Road is the main road of New Haidong Town in Dali City where the Zhonghecun tunnel is located. The design level is the first-classed, and design speed is 60 kilometres per hour. The starting and ending pile number is K0+755 ~ K1+755, and the length of the dividing line is 1,000 m; the whole tunnel is located in a straight line; the longitudinal slope of the section of the tunnel is -1.181%; the maximum buried depth of the tunnel is about 132.6m, and the surrounding rock of the tunnel site is mainly based on the V level, with the16-m tunnel span and the 7-m height. It belongs to typical large section soft rock tunnel.

4.1. Tunnel reserve deformation values

Through the specification and design data of the ground surface, the reserved deformation value of the tunnel is shown in Table 1. By comparing, the reserved deformation of Zhonghecun tunnel is taken as 15cm.
### Table 1. Value of reserved deformation

| Method                          | Reserve deformation (mm) | Vault | Surrounding |
|--------------------------------|--------------------------|-------|------------|
| Design data                    | 150                      | —     | —          |
| Code for design of Highway tunnels | 120~150                 | —     | —          |
| Technical Specifications for Bolt shotcrete support | 102~270                 | —     | —          |
| French Ministry of industry    | 100~200                  | —     | —          |
| Soviet method                  | 25.5~39.2                | 3.14~5.59 | —          |

According to the monitoring data of Zhonghecun tunnel site shows that shallow section deformation is greater than the design of reserved deformation, resulting in tunnel invasion. It causes the tunnel clearance section does not meet the design requirements. During the later process, the excavation in the tunnel will adversely affect the stability of the surrounding rock, prone to collapse. It causes a great threat to the construction personnel and equipment. Statistical analysis of multi-group section deformation found that the methods listed in the table cannot be well applied in Zhonghecun tunnel.

We try to predict the deformation of the tunnel more accurately, with a more reasonable range of the amount of reserve deformation. According to the data and field monitoring data, the deformation amount of surrounding rock is determined under the condition of certain quality assurance rate, and the numerical result of reserve deformation and the guarantee rate of on-site monitoring are used to determine the reasonable reserve deformation amount range value, the reasonable adjustment and optimization of the amount of reserved deformation in the late stage of the combination of the field monitoring data. Furthermore, it will be applied to the tunnel excavation process.

#### 4.2. Determination of reserved deformation of tunnel based on the quality guarantee rate

The design of Zhonghecun tunnel reserved deformation is 150 mm in the early stage of the construction process, referring to the design value of outer contour of the tunnel excavation. During the construction of the shallow buried section of the tunnel, it is found that the deformation of the tunnel due to excessive deformation after tunnel excavation has caused tunnel intrusion, initial support cracking and block loss phenomenon. It seriously threatens the safety of construction personnel and equipment. According to site survey and monitoring measurements, the deformation of 15cm cannot meet the deformation needs of tunnel excavation. The deformation due to excessive tunnel excavation has to install temporary support shown in Fig. 2, limiting the tunnel deformation caused by excessive invasion and preventing collapse.

![Temporary support measures in tunnel](image)

**Figure 2.** Temporary support measures in tunnel

On this basis, the monitoring data are analyzed to analyze the deformation law and the deformation of the surrounding rock of the tunnel. Based on this, the deformation range of the surrounding rock mass is deduced and the reasonable reserve deformation of the tunnel is determined. Based on the tunnel monitoring measurement data to select the 200-m length of the tunnel entrance section of the
tunnel, the monitoring data in the K0+955~K0+755 range of the section length is used as the source of analysis. In a group of displacement monitoring section, the decoration in the vault position is properly encrypted vault deformation monitoring stations, and a total of 100 sets of data vault displacement is performed.

Considering the complexity of the influence factors of large deformation of soft rock tunnel surrounding rock, there is a certain dispersion of the monitoring data of tunnel site. Based on the above factors, it is considered that it is feasible to take the range of the tunnel arch displacement as a reasonable value interval of the reserved deformation under the conditions of certain guarantee rate. The frequency-precipitation interval histogram is made based on the statistical results (See Fig. 3). According to the monitoring data of the 100 sections of the statistics, the distribution of the settlement value of the vault is approximately normal distribution, and the data distribution is relatively concentrated.

![Figure 3. Final displacement distribution of the vault](image1)

![Figure 4. Scatter plots of monitoring data](image2)

From Fig.3, the vault settling interval can be roughly divided into three grades: Class I [100, 250] accounted for more than 15%; II [50,100] and accounted for 5% to 15%; III [250,350] accounted for less than 5%. The number of vault settlement values distributed in the I-class interval is 66; the number of sections in the II-class interval 26; the number of sections in the III-level interval 8. Sedimentation value of 0-50 mm interval number proportion is 1%, which is the smallest interval probability distribution, and arch deformation in 50mm is in disproportion; that of 150-200 mm to the largest distribution probability of the interval is 26%, with the vault displacement deformation distribution in the maximum probability of this range.

The distribution interval of the displacement and deformation of the tunnel arch crown follows a certain rule. The distribution is relatively concentrated, so it is reasonable and feasible to determine the value of the reserved deformation under the condition of certain guaranteed rate. Under the condition of V-class surrounding rock in Zhonghecun tunnel, according to the field measured vault displacement data, the scatter plots of relative guarantee rate reference value of different reserved deformation conditions are drawn by statistical analysis (See Fig. 4).

Fig. 4 shows that the deformation of 25, 30, 35 and 50 cm, and its guaranteed rate are 72, 81, 93 and 100%, respectively. Taking into account the high rate of guarantee while also taking into account the cost of the loss caused by digging, based on the field monitoring measurement and construction site survey, it is more appropriate for the V level surrounding rock section of the amount of reserved deformation value of the scope of 30~35cm. Together reserved deformation numerical simulation results and monitoring data reliability conditions determine the results that the grade V best reserved rock deformation Zhonghecun tunnel is 30 cm.

5. **Engineering application and verification of the reserved deformation of Zhonghecun tunnel.**

According to the analysis of monitoring data, under condition of Zhonghecun tunnel V grade surrounding rock, the amount of reserved deformation is 30c.
Figure 5. Increase the amount of reserved deformation

In K0 + 965, it begins to set aside the deformation changing from 15 to 30 cm, and in the original design of the excavation contour will be the basis of the tunnel excavation contour extended to 30 cm. Fig. 5 shows the design of open contour adjusts the amount of deformation after the excavation contour comparison chart. The displacement monitoring points from K0+965 to K0+985 section is 20 m. Table 2 shows the monitoring data in, and Fig. 6 the vault displacement.

Figure 6. Displacement time curve of vault

According to the Fig. 6, in 20m range, K0 + 985 section of vault displacement value is up to 30.6 cm, beyond the reserved deformation of 0.6 cm; K0 +965 section arch minimum displacement 27.8cm; the tunnel over-digging 2.2cm. All belong to the 30cm reserved deformation plus or minus 10% range of acceptable deformation.

Table 2. Vault displacement data

| Mileage  | Vault cumulative displacement /mm |
|----------|----------------------------------|
| K0+965   | 278                              |
| K0+970   | 301                              |
| K0+975   | 297                              |
| K0+980   | 292                              |
| K0+985   | 306                              |

After adjusting the reserved deformation, the tunnel due to the deformation invasion of the phenomenon is significantly less, setting 30 cm reserved deformation to achieve expected results. In the K0+965~K0+985 section of the tunnel excavation, By adjusting the reserved deformation of the tunnel set to 30cm, in the tunnel construction process, it has been monitored and measured. The total amount of deformation is controlled within 30cm, feasible to determine the deformation of tunnel under a certain quality assurance rate based on monitoring measurement method.
Acknowledgments
This work was financially supported by the National Natural Science Foundation of China (11862010) and Program for Innovative Research Team (in Science and Technology) in University of Yunnan Province.

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