Optimization of tunnel construction parameters in soft rock section with high geostress

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Abstract—large deformation and even collapse are prone to occur in tunnel crossing high geostress soft rock section, which seriously restricts the construction progress. Therefore, it is necessary to optimize the construction parameters of high geostress soft rock section by bench method. Based on the Wu Nv Feng extra-long tunnel, this paper calculates and analyzes the surrounding rock deformation and structural stress under different excavation height, excavation length and excavation footage. The analysis shows that 2 / 3 h upper bench height can balance the influence of bench height on construction mechanics and construction convenience; considering the construction mechanical characteristics and excavation support time, the excavation height and excavation footage should be reduced as much as possible. Reasonable bench parameters play an important role in controlling the deformation of soft rock tunnel under high geostress, which can provide reference for tunnels with similar engineering geology and construction environment.

1. INTRODUCTION
With the development of highway construction, it is inevitable for tunnel engineering to pass through weak surrounding rock with high ground stress and complex geological conditions. Due to the obvious redistribution of excavation stress and low bearing capacity, large deformation and even collapse are prone to occur in the construction process. It is difficult for the engineering circle to seriously restrict the construction period. The bench method is widely used in highway tunnel because of its flexible construction, strong adaptability and fast construction speed. However, the bench method construction is often restricted by the geometric parameters such as step height, length and excavation footage. Taking different geometric parameters under different geological conditions will cause different stratum deformation and settlement. Therefore, it is necessary to carry out bench method construction in soft rock section with high ground stress. It is necessary to optimize the parameters\[1-5\].

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At present, many scholars at home and abroad have carried out a lot of research on the construction parameters of bench method. Wang Ming sheng [6] (2009) used the finite element numerical simulation analysis to analyze the deformation law of surrounding rock and the distribution range of plastic zone of high ground stress tunnel bench method under different bench length and with or without core soil, and then put forward reasonable bench length and core soil length. Song Shu guang, Li Zhu cai et al. [7] (2011) studied the law of mechanical effect in the construction process of super large section tunnel with weak and broken surrounding rock, and proposed the concept of step height optimization from the perspective of displacement. Based on Renhechang Tunnel, Zou Cheng lu [8] (2013) and others optimized the upper bench excavation height of bench method by numerical simulation method, and compared and analyzed the influence of five different excavation heights on the tunnel initial lining and surrounding rock. The research shows that it is good to adopt 0.65h bench height in construction, which has reference significance for future projects. Lu Feng [9] (2013) carried out numerical calculation on the upper and lower step tunnel, analyzed the displacement influence law and plastic zone distribution of vault, arch foot, side wall, arch waist and inverted arch under different excavation distances, and concluded that the change of bench method length has the greatest impact on vault settlement; Zhao dian jin [10] (2014) combined with a tunnel bench method construction of Lanzhou Chongqing railway, carried out by using finite analysis software Through the numerical simulation of three bench excavation, through the analysis of surrounding rock deformation and lining structure stress, it is concluded that the supporting parts and supporting measures should be strengthened, and the feasibility of the actual project is proved. Li Yan zong [11] (2015) took the step method tunnel construction of a railway tunnel as an example, established a numerical simulation analysis model, and analyzed the reasonable step parameters under different bench height and step length parameters, which played an important role in controlling surrounding rock deformation and reducing cost. Dai Cong [12] (2018) carried out numerical simulation under different excavation footage and bench length through FLAC3D software, and analyzed and obtained the optimal bench parameters by comparing the deformation around the tunnel and the area of plastic zone.

In view of the above research content, there are few studies on the optimization of construction parameters of high ground stress tunnel bench method. In this paper, relying on the WuNvFeng tunnel as the supporting project, through FLAC3D finite difference software, the numerical simulation of bench method under different excavation height, length and excavation footage geometric parameters is carried out, the variation law of surrounding rock displacement and the stress condition of supporting structure are analyzed, and the construction parameters of high in-situ stress soft rock tunnel are optimized, which has reference significance for future projects.

2. PROJECT OVERVIEW
WuNvFeng extra-long tunnel of ji’an-tonghua section of ji’an-tonghua section of He Da expressway is located in the south of southwest section of Lao ling mountains in the southeast of Jilin Province and in the north of Yalu Jiangxi Province. It belongs to low mountain landform of erosion structure. The tunnel site belongs to the continental climate of north temperate zone, and the south of Lao ling has obvious semi continental marine monsoon climate. There are four distinct seasons along the line, with strong dry wind in spring, high temperature and rainy in summer, cool in autumn and cold in winter. The length of WuNvFeng tunnel is about 7.9km. The floor elevation of the left side entrance and exit is 489.15m and 632.78m respectively, and the floor elevation of the right side is 486.88m and 633.86m. After the completion of the tunnel, it will become the longest highway tunnel in Northeast China. There are many bad geological sections in the construction process, and the conditions are complex. The main adverse geological conditions include weak surrounding rock, fault fracture zone, water gushing and possible high ground stress hard rock burst.

3. MECHANICAL PARAMETER TEST OF SURROUNDING ROCK
The purpose of this test is to measure the deformation parameters (elastic modulus E, Poisson's ratio U) and strength parameters (cohesion c, internal friction angle φ) of tuff. Test 1: the elastic modulus E and
Poisson's ratio $U$ of tuff were measured by uniaxial compression deformation test. The specimen size was a standard cylinder with diameter of 50 mm and height of $H = 100$ mm. The rock600-50htplus multi-functional rock triaxial test system of geotechnical Laboratory of Chongqing University was adopted. The loading speed was set at 0.01mm/min and the confining pressure was 0mpa. Test two: through triaxial compression deformation, the loading rate was set at 0.01mm/min The cohesive force $C$ and internal friction angle of tuff are measured by t-test. The specimen size is a standard cylinder with diameter of 50 mm and height of $H = 100$ mm. Rock600-50htplus multi-functional rock triaxial test system in geotechnical Laboratory of Chongqing University is adopted. The loading speed is set at 0.01mm/min, and the confining pressure is 5MPa, 10MPa, 18Mpa, 25MPa and 30MPa respectively.

The main results obtained from the test are summarized in TABLE I, which provides necessary parameters for finite element simulation of excavation calculation.

| Deformation parameters | Elastic modulus $E$ / MPa | 31400.07 |
|------------------------|--------------------------|----------|
|                        | Poisson's ratio $u$      | 0.1802713|
|                        | Uniaxial compressive strength $CS$ / MPa | 127.00 |
| Strength parameters    | Cohesion $c$ / MPa       | 23.19    |
|                        | Internal friction angle $\phi$ / ° | 48.72° |

### TABLE I. SUMMARY OF TEST RESULTS

4. NUMERICAL ANALYSIS.

4.1. step height size selection

According to Saint Venant's principle, in order to reduce the influence of boundary conditions on the calculation results, the left, right and lower boundary length of the model is taken as 60m, and the longitudinal length of the tunnel is 30m. The upper boundary height is consistent with the buried depth of the tunnel. Combined with the engineering practice, it is taken as 140m. The grid division of different bench heights is shown in Figure 1. In the calculation of step height, four different heights of upper step are taken, which are $1/3 \, h$, $1/2 \, h$, $2/3 \, h$ and $5/6 \, h$, respectively.

Figure 1 Mesh generation of different step heights
During the simulation process, the rock mass adopts solid elements, and the Mohr-Column model is used for simulation. The shell element is used for the initial support, and the elastic model is used for simulation. The second liner uses solid elements and the elastic model is used for simulation. The specific parameters of the model are shown in TABLE I.

4.1.1. Displacement analysis of surrounding rock
The curve of vault subsidence and invert uplift with excavation height under different upper bench heights is shown in the Figure 2 below.

![Figure 2](image1)

**a) Vertical displacement of surrounding rock**
**b) Horizontal displacement of surrounding rock**

Figure 2 Surrounded rock displacement analysis

After the completion of tunnel excavation, the vertical displacement of surrounding rock increases linearly with the height of upper step, the range of vault subsidence is 37mm, and the range of inverted arch uplift is 18mm. The variation of tunnel excavation displacement due to the height of upper steps accounts for 10% ~ 15% of the total deformation. The influence of different bench height excavation on the horizontal displacement of surrounding rock is small, and the horizontal displacement is relatively small when the upper bench height is taken as 2/3 h.

4.1.2. Initial support stress analysis
The initial support stress under different upper step heights is shown in the Figure 3

![Figure 3](image2)

**a) Analysis of Axial Force of Unit Initial Support**
**b) Analysis of the Bending Moment of the Initial Ring**

Figure 3 Analysis of internal forces of initial support
When the height of the upper step increases from 1/2 h to 2/3 h, the maximum initial support axial force decreases by 2.3 MN/m, which indicates that the change of bench height has great influence on the axial force of initial support. The range of positive bending moment is 0.6MN/m, and the range of negative bending moment is 0.4 MN/m. because the thickness of the initial support is about 0.5m, the increase or decrease of bending moment has great influence on the internal and external stress. Therefore, the bending moment should be reduced as much as possible when the step height is arranged.

To sum up, when determining the bench height, generally speaking, the upper step height should be increased as much as possible to reduce the structural stress. However, considering that the increase of the excavation height will inevitably lead to the decrease of the excavation support speed in the construction process, the form of support applied at one time in the simulation process lacks the consideration of the construction time. The step height can be 2/3 h.

4.2. study on the selection of upper step length

There are four different lengths of the upper steps, namely 3.0m, 4.5m, 6.0m, 7.5m. The surrounding rock conditions, boundary types and excavation conditions of different models are the same. The specific parameters of the model are shown in TABLE I. The four different excavation parameters have the same values.

4.2.1. Displacement analysis of surrounding rock

The results show that the larger the step length is, the greater the subsidence value and uplift value are. The subsidence value difference is 56mm, and the uplift value range is 64mm, which accounts for about 1/5 of the total settlement value and the total uplift value. The step length has a great influence on the vertical displacement of surrounding rock. The horizontal displacement of excavation surrounding rock with different bench length is small, so it can not be taken as the key control object in the construction process.

![Figure 4: Surrounding rock displacement analysis](image)

a) Vertical displacement of surrounding rock  
b) Horizontal displacement of surrounding rock

4.2.2. Initial support stress analysis

When the step length increases, the circumferential axial force of the initial support structure increases first and then decreases. When the step length is 4.5 m, the maximum
The length of steps has a great influence on the settlement of surrounding rock arch crown. The increase of step length will lead to rapid increase of vault settlement, less influence on the horizontal displacement of surrounding rock and less influence on the force of initial support structure. Therefore, in order to prevent the collapse of arch crown due to excessive settlement of arch crown, the step length should be reduced as far as possible. Considering the actual engineering construction situation, the step length should be taken into account It is 3m.

4.3. excavation footage study
Two types of excavation footage of 1.5m and 3.0m were taken respectively, and the surrounding rock conditions, boundary types, and excavation conditions of different models were the same. The specific parameters of the model are shown in TABLE I. The four different excavation parameters have the same values.

4.3.1. Displacement analysis of surrounding rock
The displacement values of surrounding rock under different excavation footage are shown in TABLE II.

| Excavation footage | Vault settlement | Invert heave | Horizontal sidewall displacement |
|--------------------|------------------|--------------|----------------------------------|
| 1.5                | 261              | 320          | 43                               |
| 3.0                | 231              | 365          | 62                               |

Compared with the vertical deformation of surrounding rock, it can be seen that the increase of excavation footage will lead to the increase of surrounding rock invert uplift, and the increase of excavation footage will make the surrounding rock be limited by the initial support when the pre convergence deformation is not fully developed, thus limiting the vertical displacement, which is manifested as the increase of step length and the decrease of arch crown displacement. At the same time, with the increase of excavation footage, the stress release range of surrounding rock is enlarged, and the spatial effect of open excavation section and support stable section on the free face of surrounding rock decreases, which shows that the horizontal displacement increases.

4.3.2. Initial support stress analysis
The initial support stress analysis under different excavation footage is shown in TABLE III.
TABLE III Analysis of internal forces of initial support

| Excavation footage | Circumferential axial force | Circumferential positive bending moment | Circumferential negative bending moment |
|-------------------|-----------------------------|----------------------------------------|----------------------------------------|
| 1.5               | 12.3                        | 1.72                                   | 2.20                                   |
| 3.0               | 13.4                        | 1.09                                   | 1.89                                   |

It can be seen from the figure that the increase of step length will increase the circumferential axial force of the initial support, which is not conducive to the stability of the initial support. With the increase of excavation footage, the length of the first longitudinal forming can be increased, the stress concentration at the lap joint can be reduced, and the maximum positive (negative) bending moment can be reduced.

To sum up, the increase of excavation footage is beneficial to reduce the displacement of surrounding rock vault and the circumferential moment of initial support, but it is not conducive to the uplift of surrounding rock inverted arch and the circumferential stress of initial support. Considering the actual excavation process, the influence degree caused by the increase of bench length is more unfavorable than the calculation result. In the construction process, in order to control the deformation of surrounding rock and stabilize the initial support, it is necessary to reduce the excavation footage as much as possible, enhance the timeliness of support construction after excavation, and prevent the collapse of arch crown and the instability and damage after the support is completed.

5. CONCLUSION
In this paper, based on the high geostress soft rock section of WuNvFeng extra long tunnel, through numerical analysis of the surrounding rock deformation and structural stress under different excavation height, length and excavation footage, the following conclusions are drawn:

(1) Considering the influence of step height on construction mechanics and construction convenience, the upper step height can be 2/3 h.

(2) The length of the steps has a great influence on the displacement and settlement of the arch crown, but has little influence on the horizontal displacement of the surrounding rock and the stress of the structure.

(3) The increase of excavation footage can reduce the displacement of surrounding rock vault and the negative bending moment of structure ring, but increase the uplift of inverted arch and the axial force of structure ring. At the same time, with the increase of excavation footage, the excavation and support time is longer. Considering comprehensively, in order to control the deformation of surrounding rock and stabilize the initial support, the excavation footage should be reduced as much as possible, the timeliness of support construction after excavation should be enhanced, and the vault collapse and instability damage after support completion should be prevented.

(4) Through comparative calculation, the reasonable construction parameters of bench method in WuNvFeng extra long tunnel are obtained. Combined with the field application, the excavation parameters of bench method in soft rock section with high geostress determined in this paper are reasonable and safe, which can provide reference for tunnels under similar geological and construction environment.

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