Parameter optimization of corrugated steel initial support structure of mountain tunnel based on sensitivity analysis

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Abstract. New corrugated steel initial support in mountain tunnels, as a kind of assembly structure, can achieve purposes of rapid construction, green environmental protection. However, optimization design of corrugated steel initial support in mountain tunnels is seldom researched. In this paper, Qipanshan Tunnel in Yunnan Province is taken as engineering background. Numerical simulation calculation is carried out by ABAQUS. Combined with sensitivity analysis of tunnel convergence, internal force of corrugated steel and second liner, the design parameters of wave thickness, wave height and wave pitch of initial support of corrugated steel are optimized. Research shows that sensitivity analysis method can be applied well in the optimization of tunnel initial support parameters. Effectively improving internal force of corrugated steel and secondary lining can be achieved by adjusting thickness of corrugated steel. Optimization effect of parameters of corrugated steel is more obvious in the RDP range of 0.333 ~ 0.375.

1. Introduction
With continuous development of economy, improvement of comprehensive national strength and application of high and new technology, unprecedented rapid development is achieved in Chinese tunnel engineering. Mountain tunnels occupy an important position in tunnel construction. Due to good mechanical properties of fabricated corrugated steel structure, corrugated steel has been widely used in many fields such as shed holes, bridge culvert reinforcement, and integrated pipe porches. Peng, S.Q. established a common bearing model of steel corrugated structure-soil, according to the Meriyanov calculation model. Corrugated plate was simplified into a fixed arch structure, which became a kind of plane strain problem[1]. Jiang, X.M. combined experimental research and engineering practice of corrugated steel pipe culvert of a secondary road in Inner Mongolia. And mechanical properties of corrugated steel structure were calculated and analyzed by Ansys finite element software. It was verified that corrugated steel pipe culvert has many advantages such as convenient construction, short cycle and good mechanical properties[2]. Chan, C.L. and so on compared bearing capacity of corrugated steel sheets under 16 different working conditions with different widths, thicknesses and different radii through test. Effect of width, thickness and radius on overall performance was obtained[3]. Mu, Z.H., figured out influence laws of equivalent stress, vertical stress deflection, longitudinal stress, maximum principal stress and transverse stress based on different web parameters of corrugated steel (corrugated
steel wave height, straight section length, web thickness height, etc.) by finite element analysis method[4].

Figure 1. Corrugated steel initial support structure

However, application of fabricated corrugated steel structure in initial support of mountain tunnel is still rarely involved. In this paper, Qipanshan Tunnel in Yunnan Province is taken as engineering background. Numerical simulation calculation is carried out using ABAQUS. Combined with the sensitivity analysis of rock around the tunnel, internal force of corrugated steel and internal force of the second liner, the design parameters of wave thickness, wave height and wave distance of initial support of corrugated steel are optimized. It is conducive to promote of application of the new initial support structure of corrugated steel, and tunnel technology innovation, which has a wide range of development and application prospects.

2. Project overview
Qipanshan Tunnel is located in Chengjiang-Jiangchuan Expressway in Yunnan Province (K47+200-K49+250), which is designed as a separate two-lane long tunnel. Starting and ending of the left tunnel is ZK47+212~ZK48+460, with a total length of 1248 meters and a maximum depth of 131 meters. That of the right tunnel is YK47+205~YK48+460, with a total length of 1255 meters and a maximum depth of 119 meters (Figure 2). Tunnel section passes through strata of Upper Sinian Dengying Formation, dolomitic limestone, dolomite and other rocks. The tunnel site is located in the west wing of Heishan Mountain syncline. The rock formation is 130° ±25°. The rock mass is slightly open, with a rough surface and no filling. Surface gully, dissolution tank and bud are developed. The surrounding rock grade is Grade IV.

Figure 2. Overview expressway from Chengjiang to Jiangchuan

3. Numerical simulation
3.1. Surrounding rock
Typical section is selected, with a depth of 81m (upper boundary). The lower boundary to the bottom of pore is 5 times height of pore, and the left and right borders to the wall of pore is 5 times. Surrounding rock grade of tunnel is Grade IV. The greater the buried depth is, the better the mechanical properties are. So surrounding rock is divided into five layers from top to bottom. According to the "Code for Highway Tunnel Design (JTG_D70-2004)", the mechanical parameters of five layers of surrounding rock are as shown in the following table. Mohr-Coulomb model is adopted as rock model.

| Layer | Rock grade | Thickness (m) | Bulk weight (kN/m³) | Elastic Modulus (GPa) | Poisson’s ratio | Internal friction angle (°) | Cohesion (MPa) |
|-------|------------|---------------|---------------------|----------------------|----------------|----------------------------|----------------|
| 1     | IV         | 33            | 20                  | 1.8                  | 0.32           | 27                         | 0.20           |
| 2     | IV         | 33            | 21                  | 2.3                  | 0.32           | 28                         | 0.30           |
| 3     | IV         | 39            | 22                  | 2.8                  | 0.32           | 30                         | 0.40           |
| 4     | IV         | 22            | 23                  | 3.3                  | 0.32           | 32                         | 0.50           |

3.2. Corrugated steel
Equivalent of corrugated steel plate is converted into a rectangular section beam according to reference [5], and the calculation formula is \( h = \sqrt{\frac{12ηI}{A}} \), where, \( I \) is moment of inertia of the corrugated steel plate section, \( η \) is equivalent stiffness coefficient, \( A \) is area of the corrugated steel plate section per metre, and \( h \) is equivalent thickness of the rectangular beam section, \( b \) is equivalent width of the rectangular section beam. Corrugated steel is selected as 380mm × 140mm × 5mm. \( h_{eq} = 157 \)mm and \( b_{eq} = 41 \)mm can be calculated according to the reference [5].

3.3. Concrete and anchor
Grade of concrete behind the corrugated steel is C20. Elastic modulus is \( 2.55 \times 10^7 \)MPa. Critical yield stress is \( σ_y = 9.6 \)MPa. Concrete thickness is 5cm; Grade of second lining concrete is C30. Elastic modulus is \( 3.0 \times 10^7 \)MPa, and thickness is 35cm. The anchor angle is 15°, located at arch foot and arch waist; Actual bolt diameter is 42mm, and the bolt spacing is 1.52m. Diameter of bolt is 38mm per meter after conversion.

3.4. Contact relationship
Anchor rod driven into surrounding rock is simulated by Embedded way, and the end of bolt is connected with corrugated steel by tie. The coefficient of friction between the surrounding rock and shotcrete behind the corrugated steel is \( μ = \tan(30°) = 0.58 \). The coefficient of friction between corrugated steel and the back sprayed concrete is \( μ = 0.73 \) [6].
4. Sensitivity analysis

4.1. Basic principle of sensitivity analysis

Single factor analysis method is used in sensitivity analysis. Final system characteristics of the project \( P \) are determined by \( n \) factors \( a = (a_1, a_2, \ldots, a_n) \), namely system characteristics \( P = f(a_1, a_2, \ldots, a_n) \).

When a project baseline state is set, which means that \( a = (a_1, a_2, \ldots, a_n) \), the system characteristics \( P = f(a_1, a_2, \ldots, a_n) \) is progress state which best matches the actual project. Maintain one of the influencing factors within its allowable range, and keep other impact factors fixed. The trend and degree of the system characteristics deviating from the baseline status of the project due to the change of the influencing factors can be analyzed[7].

With different factor variables \( X_{L,x} \), the sensitivity coefficient can be calculated as Equation (1):

\[
\eta_{sa} = \left( \frac{f(X_{L,x}) - f(x)}{f(x)} \right) \times 100\% = \left( \frac{X_{L,x} - x}{x} \right) \times 100\% \tag{1}
\]

4.2. Wave thickness of corrugated steel

Wave thickness of corrugated steel is selected as the variable to analyze sensitivity of the tunnel convergence, corrugated steel internal force and secondary lining internal force respectively. Initial support parameters of the actual tunnel corrugated steel are selected as reference parameters of the sensitivity analysis, which means that the corrugated steel model is 380mm \( \times \) 140mm \( \times \) 5mm, and the reference parameter is used as the intermediate value of the parameter change. On the basis of the intermediate values, wave thickness of corrugated steel of 3 mm, 4 mm, 5 mm, 6 mm, 7 mm, 8 mm, 9 mm, and 10 mm were selected as the raw data for sensitivity analysis. A large number of numerical simulations were carried out by using ABAQUS finite element analysis software, and the numerical simulation results were brought into Equation (1). The sensitivity of each control point to the circumferential convergence, corrugated steel internal force and secondary lining internal force of each corrugated steel thickness was obtained, as shown in Figure 4.
Figure 4 shows that sensitivity from wave thickness of corrugated steel to tunnel convergence, the internal force of the corrugated steel and second lining are different. The sensitivity degree of the corrugated steel wave thickness to the internal force of the corrugated steel and the second lining is greater than the sensitivity to the tunnel convergence. Therefore, in the design of corrugated steel initial support design of mountain tunnel, the purpose of effectively improving internal force of the corrugated steel and the secondary lining can be achieved by adjusting the thickness of corrugated steel. Effect of improving the deformation of the tunnel by changing thickness of the corrugated steel is not obvious.

4.3. Wave height - wave pitch of corrugated steel

Larger wave pitch and higher wave depth don’t necessarily mean more undulation of the corrugated steel, however, RDP can characterize the undulating shape better. Concept of "RDP" (Ratio of Depth to Pitch) of corrugated steel is proposed as Equation (2).

$$RDP = \frac{\text{Depth}}{\text{Pitch}} \times 100\%$$

RDP of corrugated steel is selected as the variable to analyze sensitivity of the tunnel convergence, corrugated steel internal force and secondary lining internal force respectively. Initial support parameters of the actual tunnel corrugated steel are selected as reference parameters of the sensitivity analysis. Reference parameter is used as the intermediate value of the parameter change. According to Equation (2), RDP = 0.275 (200mm×55mm×5mm), 0.333 (150mm×50mm×5mm), 0.367 (300mm×110mm×5mm), 0.375 (400mm×150mm×5mm) were selected as the raw data for sensitivity analysis. A large number of numerical simulations were carried out by using ABAQUS, and the numerical simulation results were brought into Equation (1). The sensitivity of each control point to the tunnel convergence, corrugated steel internal force and secondary lining internal force of each corrugated steel thickness was obtained, as shown in Figure 5.
Figure 5 shows that RDP has the same tendency but different sensitivity to tunnel convergence, corrugated steel internal force and secondary lining internal force. RDP has more sensitive degree to corrugated steel internal force than to second lining internal force and tunnel convergence. Optimization effect of parameters of corrugated steel initial support in mountain tunnel is more obvious in the RDP range of 0.333 ~ 0.375. Therefore, it is possible to effectively improve the internal force of corrugated steel by adjusting the wave height and wave pitch of the corrugated steel in the RDP range of 0.333 to 0.375. In addition, RDP of the corrugated steel has no obvious effect on improving the tunnel deformation and internal force of second lining.

5. Conclusion
1) In the design of corrugated steel initial support design of mountain tunnel, the purpose of effectively improving internal force of the corrugated steel and the secondary lining can be achieved by adjusting the thickness of corrugated steel. Effect of improving the deformation of tunnel by changing wave thickness of the corrugated steel is not obvious.

2) RDP has more sensitive degree to corrugated steel internal force than to second lining internal force and tunnel convergence. Optimization effect of parameters of corrugated steel initial support in mountain tunnel is more obvious in the RDP range of 0.333 ~ 0.375.

3) Sensitivity analysis method can be applied well in the optimization of tunnel support parameters.

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