Study on Bolt Support Design for Carbonaceous Shale Tunnel of Highway at High Altitude and Cold Region

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Abstract. With the large-scale development of road traffic infrastructure, tunnel construction gradually extends to high-altitude areas such as the Qinghai-Tibet Plateau. Under the influence of environmental and climatic conditions and regional geological tectonic movement, tunnel construction in this area cannot copy the technology and experience of low-altitude areas, and special research work should be carried out in accordance with regional geological characteristics. Based on a tunnel of Gongyu Highway, the bolt support design of high-altitude tunnel is studied by numerical analysis with FLAC3D software. The results show that the arch bolt should be cancelled and the side wall and lock foot bolt should be strengthened in the bolt support of highway tunnel in high-altitude cold area. Then through multi-dimensional comparative analysis, the length, circumferential spacing and setting range of anchor rods in the carbonaceous shale highway tunnel system at high altitude and cold region, as well as the number, direction and length of anchor rods at lock feet are put forward, which provides technical support for the design and construction of the relying projects, and also provides reference for similar projects.

1. Introduction
With the rise of railway and highway construction in Qinghai-Tibet Plateau, the construction technology of tunnels in high altitude and cold areas has been paid more and more attention by engineering circles. It is well known that the Qinghai-Tibet Plateau was subjected to geological structure movement in the early stage of its formation, so the regional geological structure is quite complex. The Gonghe-Yushu Highway is the first highway built in the permafrost region of the Qinghai-Tibet Plateau to restore and rebuild the life-support line after the Yushu earthquake. The average elevation of the whole highway is about 4100 m. During its construction, the Gonghe-Yushu Highway encountered permafrost Large deformation of soil and carbonaceous shale tunnels is two major technical problems. A tunnel about 2.8km in length has become a control project which restricts the whole line through because of the problem of large deformation. Due to the large deformation problem (the average daily deformation rate is 10-30 mm, and the cumulative maximum deformation is 40-80 cm), the tunnel collapse occurs more than 30 times during the construction process, one of which is the closing collapse accident, which makes the project extremely difficult. There are several problems to be solved in the bolt support design of large deformation tunnel in carbonaceous shale. (1)
In the process of excavation and support of carbonaceous shale tunnel, compared with unsystematic bolt support, whether systematic bolt support has significant influence on the variation of vault settlement and surrounding convergence of surrounding rock. (2) In the process of excavation and support of carbonaceous shale tunnel, compared with unsystematic bolt support, whether systematic bolt has significant effect on improving the stress distribution of soft surrounding rock, and whether the influence of systematic bolt on the stress magnitude of various parts of surrounding rock is different. (3) There is no significant difference between the stress distribution and the size of the initial support structure of soft rock tunnel with and without systematic bolt support. If the system bolt is effective to improve the stability of surrounding rock, how to choose reasonable bolt support parameters? Based on this, this paper carries out relevant research work on bolt support design of Alpine carbonaceous shale tunnel, and puts forward reasonable bolt support parameters, aiming at solving the construction problems of a tunnel project and providing reference for the design and construction of similar projects.

2. Basic theory status of bolt support

In the field of tunnel and underground engineering, bolt reinforcement has played a certain role in enhancing the self-stability of surrounding rock [1]. Many engineers and researchers at home and abroad have also carried out a lot of experiments and studies on bolt support [2~4]. The mechanism of bolt support is analyzed in a deeper level, which promotes the development of bolt support technology and promotes its application in tunnel engineering. It is widely used in many fields. Of course, some scholars are skeptical [5-6], so there is much controversy. As far as the theoretical study of the supporting effect of tunnel bolts is concerned, there are two main theoretical systems.

(1) The theory of reaction restraint. The theory holds that the existence of bolts provides elastic support for the surrounding rock of tunnels and restrains the continuous deformation of surrounding rock. The representative theories of this theory mainly include neutral point theory and anchorage force theory. The neutral point theory [7~8] holds that there is a neutral point in the bolt, and there is a shear stress between the two sides of the neutral point of the bolt and the surrounding rock which increases along the axial direction of the bolt, and the direction of the shear stress is opposite to the direction of the surrounding rock deformation, which produces a restraining axial force on the surrounding rock; while the anchoring force theory holds that after the completion of the tunnel excavation bolt, the dilatancy and deformation of the surrounding rock will occur. Extruding the bolt can produce anchoring force, which can restrain the deformation of surrounding rock and enhance the stability of surrounding rock.

(2) The theory of enhancing the bearing capacity of surrounding rock. The theory regards surrounding rock and bolt as a whole for analysis. The implantation of task bolt improves the shear strength and bearing capacity of surrounding rock. The representative theories are mainly the theory of strengthening surrounding rock strength [9-10] and the theory of balanced arch. The theory of strength strengthening of surrounding rock holds that the use of bolts in surrounding rock can increase the cohesive force between rock and soil particles in the disturbed area of surrounding rock through certain compaction and compaction, thus improving the mechanical parameters of shear strength of surrounding rock; and the theory of balanced arch holds that a certain range of anchor solid anchors are formed in the interaction between bolts and surrounding rock by using the shear and sliding resistance of bolts. The action makes the loosened rock after surrounding rock deformation form a balanced arch with certain bearing capacity.

3. Research on Design of System Bolt Support Based on Numerical Analysis

3.1 Analysis Model Establishment and Parameter Selection.

In this paper, the numerical analysis system of bolt support effect and reasonable design parameters are carried out by means of FLAC3D software. The necessary parameters (length, circumferential spacing and setting range) of bolt design in the analysis work condition system are set as follows: 1.
The length of bolt has 10 working conditions: 1.0m, 2.0m in turn. 9.0m; 2) setting up four working conditions of bolt spacing: 0.6m, 0.8m, 1.0m and 1.2m; 3) According to the force mode of bolts in different parts of the system and the difficulty degree of bolting, it can be divided into three working conditions: full ring laying (tunnel arch wall 200 degrees), arch laying (tunnel arch wall 90 degrees), side wall laying (tunnel arch wall 90 degrees to 200 degrees).

Figure 1. Numerical calculation analysis model.

Considering the influence of boundary conditions, the plane strain model (Figure. 1) is adopted in this calculation. The diameter of the left and right sides of the model and the bottom boundary is 3-5 times. The top of the model is taken to the surface. The size of the model is 200 m×200 m. The Mohr-Coulomb yield criterion is adopted for the calculation and analysis of stratum materials. The stress and strain vary in the elastic-plastic range. Two steps of the tunnel are excavated, and the stress of the surrounding rock, lining of the tunnel and Mutual Coupling is taken into account. When calculating and modeling, the bolt element is used in the system bolt (grouting duct of phi 42), and the shell element is used in the initial support. At the same time, the computational grid of the tunnel and the surrounding area is refined. The displacement boundary conditions are as follows: free boundary at the top and fixed boundary at the bottom and left and right. The numerical calculation model of the tunnel is shown in Figure 1. The mechanical parameters of surrounding rock are obtained from laboratory experiments [11], as shown in Table 1.

| Number | Parameter name               | Symbol | Company | Numerical value |
|--------|------------------------------|--------|---------|-----------------|
| 1      | density                      | ρ      | kg/m³   | 2593            |
| 2      | Modulus of elasticity        | E      | GPa     | 0.201           |
| 3      | Poisson ratio                | u      |         | 0.28            |
| 4      | Cohesive force               | c      | KPa     | 88.94           |
| 5      | internal friction angle      | φ      | °       | 29.46           |

3.2 Result analysis

3.2.1 Analysis of Bolt Length. The vault settlement, surrounding convergence and maximum principal stress of initial support are extracted for different bolt lengths, and the variation of surrounding rock deformation with bolt length (Figure. 2) and the variation of maximum principal stress of initial support with bolt length are drawn (Figure. 3).
Figure 2. Variation of Surrounding Rock Deformation with Bolt Length

From Figure 2, it can be seen that the settlement of surrounding rock vault is 52.60 cm and the surrounding convergence is 70.34 cm when the system bolt is not installed in the carbonaceous shale tunnel. But when the system bolt is installed after the tunnel is excavated, the effect of controlling the surrounding rock deformation is quite obvious. Even when the length of the bolt is 1.0 m, the settlement of surrounding rock vault becomes 37.90 cm and the surrounding convergence becomes 39.08 cm. With the increase of the length of the bolt, the deformation of surrounding rock also decreases. When the length of bolt is greater than 6 m, the control effect of bolt length on the deformation of surrounding rock is not obvious. Figure 3 shows that, with the increase of bolt length, the maximum principal stress of initial support tends to decrease. When the length of bolt is longer than 6 m, the change of maximum principal stress of initial support is smaller. The system bolt is used to improve the self-supporting ability of surrounding rock, and the surrounding rock shares part of the surrounding rock pressure, thus reducing the load acting on initial support, but when the length of bolt is longer than 6 m, the bolt is used to reduce the load acting on initial support. The effect of rod action also decreases gradually. In order to facilitate further comparative analysis, the plastic zone distribution of surrounding rock with different bolt lengths is extracted, as shown in Figure 4.

Figure 3. Variation law of initial large principal stress with bolt length

Figure 4 shows that with the decrease of bolt length, the plastic zone of surrounding rock decreases. That is to say, for the tunnel of carbonaceous shale rock mass, the rock mass is loose and the bolt is implanted, on the one hand, the surrounding rock is compacted, the internal friction angle of rock mass is increased, and the shear strength of rock mass is increased, and the plastic zone of surrounding rock decreases accordingly. When the length of bolt is 6-9 m, the plastic zone of surrounding rock is close to that of surrounding rock. That is to say, when the length of the bolt is longer than 6m, the effect of the bolt will also decrease, and the control of the deformation of surrounding rock is not obvious. Therefore, when considering the displacement of surrounding rock, the internal force of supporting structure and the plastic zone, it is suggested that the reasonable length of the bolt should be 4-6m for the carbonaceous shale tunnel in the high altitude and cold zone.

3.2.2 Anchor ring spacing. The deformation of surrounding rock is extracted, when the circumferential spacing of different bolts is different, and the variation rule of surrounding rock deformation with the
circumferential spacing of bolts is drawn (Figure 5). From the analysis of Figure 5, it can be seen that in the process of increasing the circumferential spacing from 0.6m to 1.0m, the vault sinking rapidly increases, and the circumferential spacing from 1.0m to 1.2m, the increment of vault sinking is small. For the circumferential convergence, the circumferential spacing increases from 0.8m to 1.2m, there is no obvious increment. From the engineering point of view, the reduction of the circumferential spacing of anchors will prolong the operation time, which is not conducive to the timely shaping of the initial support. For deformation and construction factors, the hoop spacing of bolts should be 1.0m.

Figure 5. Variation of Surrounding Rock Deformation and Anchor Ring Spacing

3.2.3 Setting range of bolt. The results of displacement calculation of surrounding rock under different calculation conditions (Table 2), plastic zone distribution of surrounding rock (Figure 6) and axial force distribution of bolt (Figure 7) are extracted and compared. From Table 2, it can be seen that the settlement of vault and convergence of surrounding rock are smaller when the whole ring of anchor is set up than when the system anchor is set up locally. The system anchor is effective in controlling the deformation. The settlement of vault of the system anchor in the arch is smaller than that of the system anchor in the side wall, and the convergence of the system anchor in the side wall is smaller than that of the system anchor in the arch, that is to say, the systematic anchor in the arch can mainly control the settlement and deformation of the vault, while the systematic anchor in the side wall can effectively control the horizontal convergence of the surrounding rock, but the convergence and deformation control ability of the systematic anchor in the side wall is obviously better than that of the systematic anchor in the arch. At the same time, it can be seen from Figure 6 that during the construction and excavation of the carbonaceous shale tunnel, the active plastic zone of the surrounding rock mainly concentrates on the side wall, and the monitoring data show that the convergence displacement of the surrounding rock is larger than the settlement of the vault, and the surrounding rock is prone to plastic extrusion failure of the side wall. Therefore, it is necessary to reinforce the surrounding rock of the arch wall effectively. From Figure 6, it can be seen that the side wall can be effectively controlled by setting system bolts. The development of the active plastic zone of the wall reinforces the surrounding rock of the arch wall. It can be seen from Figure 7 that during the excavation of the carbonaceous shale tunnel, the tension of the system bolts appears to varying degrees, and the axial force of the bolts at the side wall is greater than that of the arch system bolts. That is to say, the function of the system bolts at the side wall is greater than that of the arch system bolts. At the same time, the closure time of the initial support is prolonged due to the difficulty in setting and installing the anchors in the arch system. Therefore, in the process of design and construction of carbonaceous shale tunnel, arch system bolt can be cancelled, side wall system bolt and lock foot bolt can be strengthened. It is suggested that system bolt should be set in the range of 90~ 200 degree of tunnel arch wall.
Table 2. Table for calculating displacement of surrounding rock under different bolt setting ranges

| Number | Bolt setting range                  | Vault settlement (cm) | Peripheral convergence (cm) |
|--------|------------------------------------|-----------------------|----------------------------|
| 1      | Full ring design                   | 29                    | 18                         |
|        | (Tunnel Arch Wall 200 Degree Range)|                      |                            |
| 2      | Arch set up                        | 33                    | 38                         |
|        | (Tunnel Arch Wall 90 Degree Range) |                      |                            |
| 3      | Side wall design                   | 38                    | 28                         |
|        | (Tunnel Arch wall in the range of 90 ~200 Degree) | | |

![Image showing distributions of plastic zone of surrounding rock and axis force of bolt.](image)

4. Research on Design of Lock-foot Bolt Support Based on Numerical Analysis

4.1 Establishment of Analytical Model and Selection of Calculating Parameters

The necessary parameters (number, setting angle and length) of the bolt design in the analysis working condition system are set up as follows: 1) the number of bolts is 2, 4, 6 and 8 in turn; 2) the angle of the bolt is set horizontally and downward; 3) the length of the bolt with lock foot is set in three working conditions: 3m, 6m and 9m in turn, and the calculation model and parameters are set up in the same 2.1 section.

4.2 Analysis of calculation results

4.2.1 Bolt quantity. In order to facilitate comparative analysis, the displacement stress eigenvalues of typical parts of surrounding rock are extracted with different numbers of bolts, and the variation of typical eigenvalues with the number of bolts is plotted (Figure 9). The plastic zone distribution of surrounding rock with different numbers of bolts is extracted for comparative analysis (Figure 10).
Figure 8 (a) shows that the deformation of surrounding rock decreases with the increase of the number of anchor bolts. When the number of anchor bolts increases from 2 to 6, the deformation of surrounding rock decreases linearly. When the number of anchor bolts exceeds 6, the influence of the increase of the number of anchor bolts on the deformation of surrounding rock decreases accordingly. From Figure 8 (b), the number of anchor bolts has little effect on the stress distribution of surrounding rock.; Figure 9 shows that with the increase of the number of bolts, the change of plastic zone of surrounding rock is not great, the plastic zone of anchor bolt at lock foot decreases, and the active plastic zone in surrounding rock decreases obviously, and the risk of instability failure of surrounding rock decreases. Based on the above, considering the stability of surrounding rock and the construction efficiency of highland tunnel, it is suggested that carbonaceous shale should be considered comprehensively. The design of tunnel lock foot bolt is preferable: 3 rows and 6 lock foot bolts are arranged at the arch foot of each step.

Figure 8. Variation of Surrounding Rock Deformation and Principal Stress with the Number of Lock-foot Bolts

![Deformation of surrounding rock](image1)
![Principal stress of surrounding rock](image2)

Figure 9. Distribution of Plastic Zone in Surrounding Rock Varies with the Number of Lock-foot Bolts

| Number | Set an angle | Vault settlement / (mm) | Peripheral convergence / (mm) | Maximum principal compressive stress/ (MPa) | Maximum principal tensile stress/ (MPa) |
|--------|--------------|-------------------------|------------------------------|--------------------------------------------|---------------------------------------|
| 1      | level        | 357.90                  | 246.89                       | 5.592                                      | 0.287                                 |
| 2      | Slantingly downword | 361.75                 | 246.74                       | 5.595                                      | 0.275                                 |

4.2.2 Lock foot bolt setting angle. In order to facilitate comparative analysis, the characteristic values of displacement stress at typical parts of surrounding rock with different number of bolts are extracted (Table 3), and the plastic zone distribution of surrounding rock with different number of bolts is extracted for comparative analysis (Figure 10).
From Table 3, it can be seen that the settlement of the vault of surrounding rock is smaller when the anchor bolt is laid horizontally than when the anchor bolt is laid, and its surrounding convergence and stress distribution are similar to those when the anchor bolt is laid slantingly downward, basically unchanged. That is to say, the control effect of the change of the anchor angle on the vault settlement is more obvious than that of the surrounding convergence. When the anchor bolt is laid horizontally, the deformation control effect is the best. At the same time, it can be seen from Figure 10 that the plastic zone of the side wall of surrounding rock is smaller when the lock foot bolt is laid horizontally than when the lock foot bolt is laid slantingly downward. It is further illustrated that the deformation control of the lock foot bolt in the carbon shale tunnel should be controlled slantingly downward when the lock foot bolt is laid horizontally. Therefore, it is suggested that the lock foot bolt be laid horizontally and the steel support is effective welding.

4.2.3. Length of lock foot bolt. In order to facilitate comparative analysis, the characteristic values of displacement and stress at typical parts of surrounding rock with different bolt lengths are extracted (Table 4), and the plastic zone distribution of surrounding rock with different bolt numbers is extracted for comparative analysis (Figure 11). Table 4 shows that the deformation of surrounding rock decreases with the increase of the length of anchor bolt, but the decrease range is small. Figure 11 shows that with the decrease of the length of anchor bolt, the plastic zone of tunnel side wall decreases obviously, and the active plastic zone also decreases. When the length of anchor bolt increases to 9m, the active plastic zone disappears completely, that is to say, the length of anchor bolt increases, and the stability of surrounding rock, with the trend of improvement, the risk of instability failure of surrounding rock decreases. Based on the above, considering the stability of surrounding rock and the construction efficiency of highland tunnel, it is suggested that the length of anchor bolt at lock foot of carbonaceous shale tunnel should be 6 m.

Table 4 Summary of Typical Eigenvalues

| Number | Bolt length/(m) | Vault settlement /(mm) | Peripheral convergence /(mm) | Maximum principal compressive stress/(MPa) | Maximum principal tensile stress/(MPa) |
|--------|-----------------|------------------------|-----------------------------|------------------------------------------|--------------------------------------|
| 1      | 3m              | 358.56                 | 256.05                      | 5.598                                    | 0.251                                |
| 2      | 6m              | 357.90                 | 246.89                      | 5.592                                    | 0.287                                |
| 3      | 9m              | 356.22                 | 242.51                      | 5.590                                    | 0.292                                |
Figure. 11 Distribution of plastic zone in surrounding rock varies with length of anchor bolt

5. Conclusion
By means of numerical analysis, this paper studies the supporting design parameters of systematic bolts and anchor bolts for highway carbon shale highway tunnels in high altitude and cold regions, and mainly draws some conclusions.

(1) The bolt implantation not only plays a role in compacting the surrounding rock, but also improves the shear strength of the loosened surrounding rock to a certain extent, so as to control the deformation. But it is not the longer the bolt is, the better the deformation is. The reasonable length of the system bolt is 4-6 m and the circumferential distance is 1.0 m. At the same time, the carbonaceous shale rock is extremely fragmented and easy to collapse due to the site construction and surrounding rock conditions. It is difficult to construct hollow grouting bolt. Self-propelled bolt is recommended.

(2) Systematic bolts in the side wall play a greater role than those in the arch system. At the same time, because of the difficulty in setting and installing the bolts in the arch system, the closure time of the initial support is prolonged. Therefore, in the process of tunnel design and construction, the arch system bolts can be cancelled and the side wall system bolts can be strengthened in the range of 90~200 degree of the tunnel arch wall.

(3) The control effect of setting angle of lock-foot bolt on vault settlement is more obvious than that of surrounding convergence. When the lock-foot bolt is laid horizontally, the effect of deformation control is the best. At the same time, with the increase of the length of lock-foot bolt, the stability of surrounding rock tends to improve, and the risk of instability failure of surrounding rock decreases. Therefore, it is advisable to lay three rows of 6 roots, 6m long φ42 grouting duck horizontally at the arch foot of each step of tunnel, and ensure effective welding with the steel shotcrete.

(4) In this paper, the design parameters of anchor bolt support for high-altitude carbonaceous shale highway tunnel are given by numerical analysis method. However, because it cannot include all the actual engineering conditions, it is only applicable to the tunnel of this relying project at present. It can be used as reference for similar projects, and further guides the follow-up engineering practice through verification and optimization of a large number of similar projects.

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