



Study on Instability Mechanisms of Straight-Arm Rock Anchor Abutments Based on Bearing Rock Bolt Monitoring

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Abstract. As a new type of underground powerhouse lifting system support structure, the straight-arm rock anchor abutments has the characteristics of light-weight structure and flexible layout. Aiming at the problem of detachment and instability between concrete abutments and rock walls, the failure mechanism of key components such as contact surface, bearing rock bolt and auxiliary rock bolt was studied, and the design idea of straight-arm rock anchor abutments was established with the bearing limit of inclined rock bolt as the key evaluation index. The research results indicate that the introduction of a horizontal auxiliary rock bolt group provides a design basis for the selection of the neutral point O on the contact surface. Compared to the structure without load-bearing rock bolt, the ultimate bearing capacity of the straight-arm rock bolt with 1-2 inclined rock bolts increased by 6% and 56.3% respectively. Under the action of upper loads, the instability of straight-arm rock bolts and abutments exhibits a progressive evolution law of contact surface strength failure, yield of load-bearing rock bolt, and instability of elastic rock foundations. The engineering monitoring datas show that when the upper design crane load is applied, the maximum axial force monitored by the integrated load-bearing rock bolt is 5.54KN, which is far below the allowable values of standard design and material performance, and the key load-bearing components of structure are in a safe and reliable service state.

Keywords: straight-arm rock bolt structure, failure mechanism, bearing limit, intelligent monitoring rock bolt

1 Introduction

Hydropower energy engineering is an important means to regulate the safe and stable operation of the power grid, and it has advantages such as being clean, environmental protection, high efficiency and stability^[1]. As the core component of hydropower energy engineering, underground powerhouses and ancillary caverns are developing towards complex structures such as large-span, high side walls, and multiple intersections^[2-5]. In the construction of underground powerhouses in hydropower stations, in order to reduce excavation and accelerate construction progress, the vast majority of

underground powerhouses adopt rock anchored crane beam structure^[6]. In recent years, with the continuous development of engineering construction demand, the new lifting system solution of 'rock anchor 'abutments+steel' structure track beam' based on optimization of traditional rock anchor beam structure has achieved good engineering application results^[7]. The rock anchor abutments refers to a combination structure in which the reinforced concrete abutments are fixed in a stable rock mass through grouting long rock bolt, so that the upper load on the abutment is transmitted to the rock mass through the long rock bolt, thereby achieving the synergistic bearing effect of the three. Compared with the traditional rock bolt crane beam, the rock anchor abutments structure has the advantages of installing the crane in advance, and has the characteristics of high economic benefit and flexible layout^[8]. According to the different forms of contact surface between concrete abutment and rock wall, the rock anchor abutments structure can be divided into rock bench type, inclined wall type and straight arm type. The construction method of straight-arm rock anchor abutments is the simplest and has a wider application prospect.

From the perspective of excavation technology, Zhang et al. ^[9] discussed the main construction difficulties and improvement measures under adverse geological conditions, and proposed suggestions such as reasonable control of layered excavation height. Luo ^[10] and Yu ^[11] analyzed the displacement change trend of surrounding rock near the rock bolt structure after excavation of each layer of the powerhouse, and proposed the construction suggestion of pre-splitting first and then pouring in layers. From the perspective of strengthening the stability of rock anchor structures, Song ^[12], Ma ^[13], Tang ^[14] studied the effects of support structures, rock burst phenomena, and geological strength indicators on local cracking phenomena of rock anchor structures during service respectively, and provided targeted crack treatment and structural strengthening measures.

Based on the above analysis, there are few studies on the instability and failure mechanism of the straight-arm rock anchor abutments structure, but the health monitoring methods carried out in combination with engineering examples are relatively simple. Based on an underground powerhouse construction project in China, this paper studied the instability and failure mechanism of the straight-arm rock anchor abutments structure. Combined with the actual engineering situation, the service state monitoring of key bearing rock bolt was carried out, and the 'four-phase synergy' bearing mode of the straight-arm rock anchor abutments structure is verified. The safety bearing control measures were put forward in order to provide useful reference for similar engineering construction.

2 Design Method of Straight-Arm Rock Anchor Abutments

When the angle β of contact surface between the concrete abutment and rock mass is 0, the rock anchor abutment is a straight-arm structure, as shown in Figure 1. Considering that the oblique bearing rock bolt in the straight-arm rock anchor abutments structure is in a local shear state, which is not conducive to the full play of material properties.

Four horizontal rock bolts perpendicular to rock wall are set up to improve the shear performance of structure, and the anti-torsion performance of the straight-arm rock anchor structure outside the plane is enhanced.

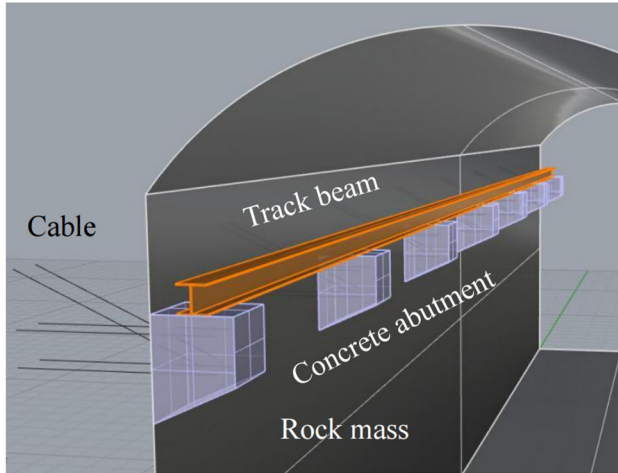


Fig. 1. Straight-arm rock anchor abutments structure

2.1 Assumption of Elastic Rock Abutments

In the initial stage of external crane load application, the concrete abutment directly transfers upper load to rock mass through contact surface. The structure can be restored to initial state if the load is unloaded at this time, and the rock mass is characterized by elastic foundation^[15-16]. As the load on upper crane increases, the cable-stayed rock bolt group gradually comes into play, transferring the load acting on the concrete abutment to the rock mass, so that the abutment, contact surface, rock bolt and rock mass work together to exert bearing capacity.

2.2 Force Analysis Model

Based on the assumption of elastic rock foundation mentioned above, the ultimate displacement method is used to solve the preliminary selection of straight-arm rock anchor abutments structure. In the analytical calculation, the resultant force point between horizontal rock bolt and contact surface is regarded as the neutral point of contact surface. The force analysis of straight-arm rock anchor abutments structure is shown in Figure 2. In the figure, F is the axial tension of upper rock bolt (N), F_v is the sum of vertical concentrated load of crane system acting on concrete abutment (N), F_h is the sum of horizontal concentrated load of crane system acting on concrete abutment (N), G is the self-weight load of concrete abutment (N), W is the gravity of upper track beam and other accessories (N), N is the reaction force of rock mass to abutment, which is triangular distribution (N), S is the anti-sliding force caused by reaction force (N); H is the

height of rock anchor abutment, namely the length of contact surface (m); $h_{0,1}$ is the distance from action point O to upper and lower ends of abutment (m), L_w represents the width of rock anchor abutment (m), L_0 represents the length of cable-stayed rock bolt group (m), θ is the slight rotation angle (rad) of the abutment around O point.

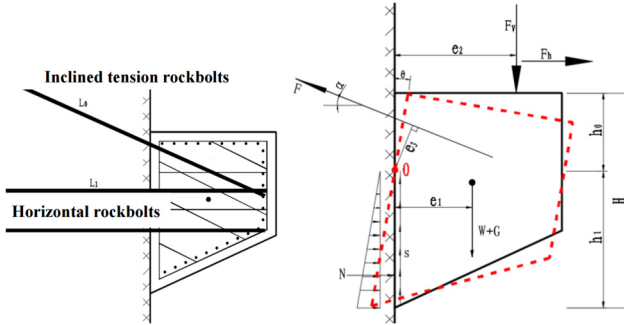


Fig. 2. Simplified model and force analysis diagram of straight-arm abutment

2.3 Structure Calculation Method

The elastic rock foundation conforms to the Winkler hypothesis, and the deformation of rock wall in the compression zone of foundation reaction force is the average elastic deformation of rock wall. Therefore, the supporting reaction force can be expressed by Eq. (1):

$$N = \frac{1}{2} Kh_1^2 L_w \theta \tag{1}$$

where, K is the elastic resistance coefficient of rock mass (kN/m^3).

According to $\sum M_0 = 0$, the moment equilibrium condition of above force can be expressed by Eq. (2).

$$N \times \frac{2}{3} h_1 + F \times e_3 = (W + G) e_1 + F_v e_2 + F_h h_0 \tag{2}$$

where, θ is small rotation angle, that is, the elongation of elastic tensile rock bolt, which can be expressed by Eq. (3).

$$\Delta L = L \theta \tag{3}$$

The axial tension of rock bolt can be expressed by Eq. (4).

$$F = EA \frac{\Delta L}{L} = EA \frac{e_3 \theta}{L_0 \cos \alpha} \tag{4}$$

By introducing equations (1), (3) and (4) into equation (2), we obtain the equation about the basic unknown quantity θ , which can be expressed by Eq. (5) and (6)

$$\frac{1}{3} Kh_1^3 L_w \theta + EA \frac{e_3^2 \theta}{L_0 \cos \alpha} = (W + G) e_1 + F_v e_2 + F_h h_0 \quad (5)$$

$$\theta = \frac{3 \left[(W + G) e_1 + F_v e_2 + F_h h_0 \right]}{Kh_1^3 L_w + 3EA \frac{e_3^2}{L_0 \cos \alpha}} \quad (6)$$

The basic displacement unknown θ is obtained from Eq. (6), so as to further obtain F, N and S, and the preliminary design parameters of straight-arm rock anchor abutments structure can be determined accordingly. Through the analysis of Figure 3, it can be found that with the increase of oblique anchor angle, the tendency of abutments structure to break away from rock wall is slowing down, which is closely related to the conversion of oblique anchor bearing characteristics from tensile effect to the suspension effect.

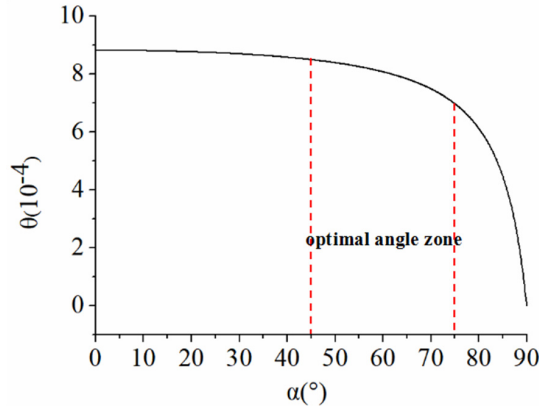


Fig. 3. Variation trend of rock bolt inclination angle and displacement

3 Study on Instability Failure Mechanism

Using finite difference software FLAC 3D for simulation analysis and calculation, the mechanical response characteristics of rock anchored abutments structures under additional loads were analyzed through processes such as model establishment, mesh division, parameter assignment, boundary condition application, and solution calculation. The spatial dimensions of straight-arm rock anchor abutments are shown in Table 1. The rock mass is grade III above average granite with burial depth of 100m. The

relevant material parameters are shown in Tables 2 and 3. The structure consists of 18696 units and 21384 grid nodes.

Table 1. Spatial dimensional parameters of straight-arm rock anchor abutments

Suspension length(L)	0.8 m
Width(H_w)	1.0 m
Facade height (H_1)	0.6 m
Slope height (H_2)	0.4 m
Rock wall angle (β)	0°

Table 2. Rock mass, concrete material parameter

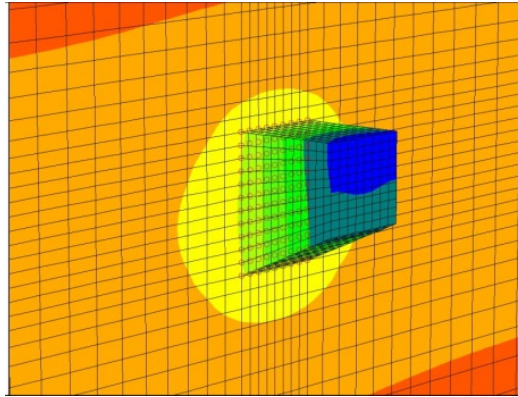
Material	Rock mass	Concrete
Elastic modulus	10	16.7
Poisson ratio(μ)	0.3	0.2
Cohesion (c)/MPa	1.2	2.75
Friction angle (ϕ)/°	43	50
Tensile strength	1.0	1.43
Density (ρ)/g·cm ⁻³	2.6	2.2

Table 3. Contact surface material parameters

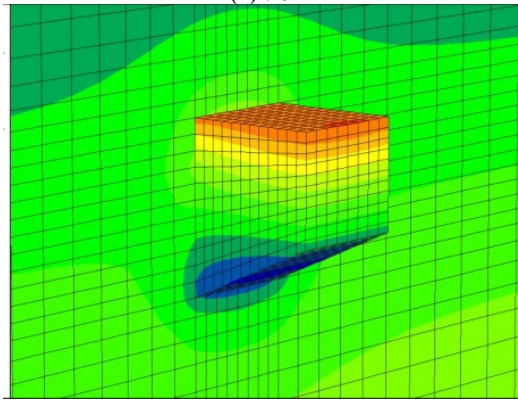
Normal stiffness (Kn)/ GPa	1e12
angential stiffness(Ks)/ GPa	1e12
tensile strength (T) /MPa	0.8
Cohesion (c)/MPa	1.2
Friction angle (ϕ)/°	40

3.1 Calculation of Bearing Limit

The load response of straight-arm rock anchor abutments structure under no rock bolt condition rod is shown in Figure 4. Key parameters were extracted for sensitivity analysis, and the calculation results are shown in Table 4. Define the compression section ratio ξ (the ratio of compression zone to contact surface area) to quantitatively characterize the contact between concrete abutment and rock wall on the contact surface. The calculation results of structural displacement and maximum stress of rock mass are shown in Figure 5. Analysis shows that, from the perspective of overall structural stability, as upper load increases, the displacement of structure in all directions also increases, and there is no significant change in displacement extremum in a single direction. When the upper load value exceeds 16 t, the structure directly undergoes instability and failure; From the connection situation of contact surface, the critical load for failure of straight-arm rock anchor abutments structure under this working condition is 16 tons.



(a) 7.5t



(b) 15t

Fig. 4. Load response of straight-arm rock anchor abutments structure under no rock bolt condition

Table 4. Response statistics of straight-arm structures

Additional load value /t	Max-Disp-Z /m	Maximum tensile stress $\times 10^5$ /Pa	Maximum compressive stress $\times 10^5$ (Pa)	Compression section ratio ξ
5	3.8553e-5	4.66	4.35	1
7.5	4.8091e-5	6.32	5.89	0.99
10	5.8522e-5	6.60	7.54	0.98
12.5	7.6419e-5	4.56	10.2	0.87
15	8.8639e-5	4.21	12.1	0.55
16	9.3233e-5	4.47	12.8	0.5
17.5	—	—	—	0.05
20	—	—	—	0

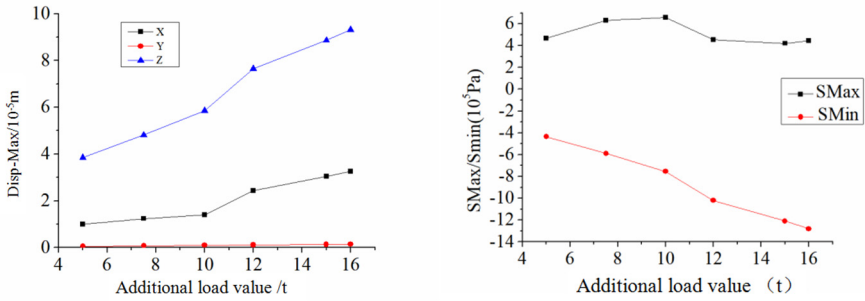
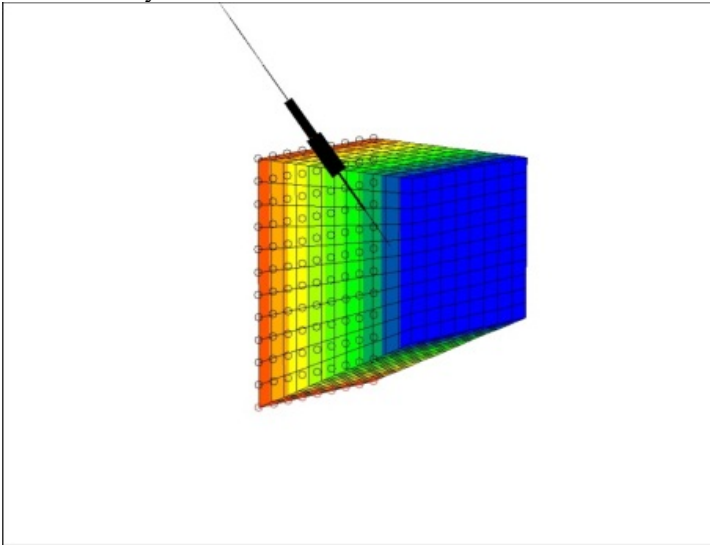


Fig. 5. Calculation results of structural response under load

The load response of straight-arm rock anchor abutments structure under condition of rock bolt application is shown in Figure 6, and the calculation result of maximum axial tension of bearing rock bolt is shown in Figure 7. Analysis shows that, under the same working conditions, applying two diagonal bearing rock bolt significantly improves bearing capacity of rock anchor abutments structure, and the structural bearing limit is increased from 16 tons to over 25 tons. Through comprehensive comparative analysis of factors such as contact surface connection, axial tensile stress of anchor rods, and structural displacement, it is determined that the ultimate bearing capacity of structure has been increased by 6% and 56.3% respectively under working conditions of single and two bearing rock bolts. In addition, the two diagonal bearing rock bolts have effectively improved the bonding ability between rock bolts and rock wall in the original structure, strengthened the connection performance of contact surface, and further enhanced reliability of structure.



(a) Single piece -17.5 t

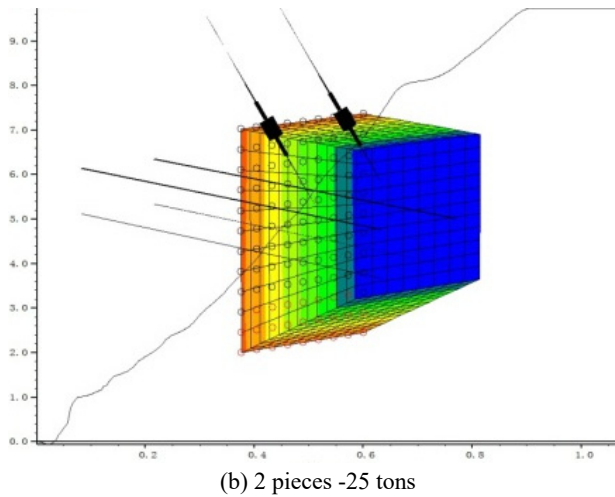


Fig. 6. Structural load response with rock bolts working condition

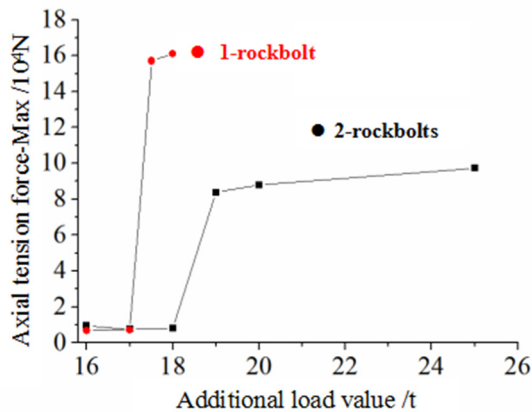
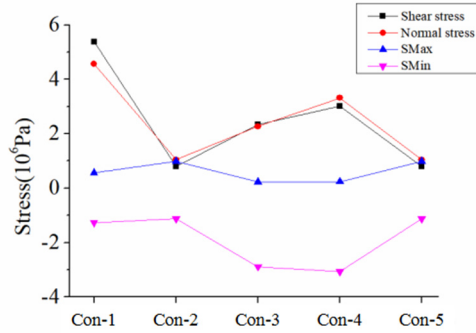


Fig. 7. Trend of maximum tensile force inside bearing rock bolt

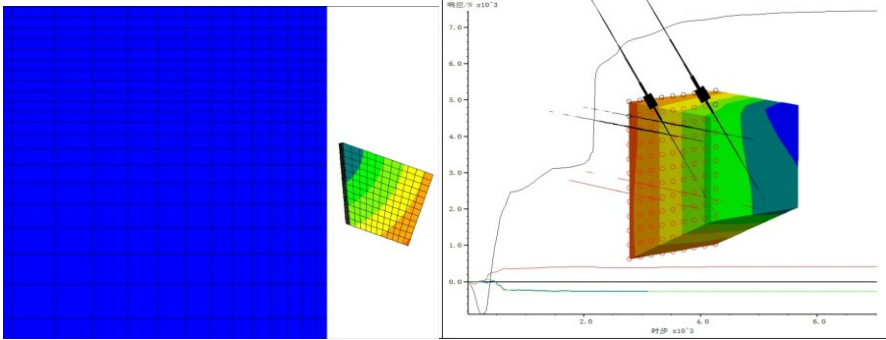
3.2 Instability and Failure Process

The influence of contact surface, bearing rock bolt selection and horizontal rock bolt arrangement on the bearing limit of straight-arm rock anchor abutments structure is investigated respectively. The calculation results are shown in Figure 8. For the X-direction displacement of structure, the straight-arm structure has a distribution of "positive top and negative bottom", that is, there is an action point O on the contact surface, which causes the entire structure to rotate at a small angle around this point. This is consistent with the logical thinking of limit displacement method in the previous analytical calculation. The clockwise flipping of structure and detachment of contact surface occur simultaneously. The detachment of structural contact surface directly

determines the timing and final form of structural instability and failure, and it's the primary factor in determining structural failure. As the load on upper crane increases, the structural failure exhibits a progressive evolution law of contact surface strength failure, yield of bearing rock bolt, and instability of elastic rock foundation.



(a) Different contact surface parameters



(b) Different rock bolt parameters and selection

Fig. 8. Structural load response with rock bolt working condition

The variation of a single parameter does not directly change failure mode of straight-arm rock anchor abutments structure. The bonding performance of contact surface directly determines the timing of detachment between rock mass and contact surface, and it's the initial factor for structural failure. While ensuring its own integrity, the rock mass indirectly affects the bearing limit of structure mainly through the bonding force with contact surface, that is, the bonding performance between relatively fragmented rock mass and contact surface will be improved. The anchorage depth and diameter of bearing rock bolt will not change the stress distribution inside structure, and when the upper load is constant, the minimum anchorage depth and diameter of bearing rock bolt are basically determined. In engineering practice, it is necessary to reasonably optimize the material selection with the highest cost-effectiveness ratio based on field engineering experience, construction equipment support conditions and personnel and equipment matching efficiency.

4 Engineering Monitoring Data Analysis

The main body of underground powerhouse is located in biotite monzonitic granite. The rock mass of tunnel is slightly weathered, the hammering sound is brittle, there is rebound, and it is difficult to break. The main developed joints are two sets of northeast trending and northwest trending joints, with closed joint surfaces and an average spacing of 0.2 m - 0.4 m. The surrounding rock is basically Class III, with relatively intact rock mass and an overlying rock mass thickness of about 100 m-150 m.

4.1 Structural Design Scheme

After calculation, the preliminary design of structure is determined as shown in Figure 9. Two inclined rock bolts are made of HRB400 steel rock bolts with 25 mm diameter and 3 m anchor depth. The longitudinal reinforcement of concrete abutments has a diameter of 20 mm @150×150 HRB400 steel rock bolts and stirrups with a diameter of 8 mm @100 mm HRB335 steel rock bolts, with four 25mm diameter HRB400 auxiliary steel rock bolts set horizontally. The design grade of concrete strength is C30.

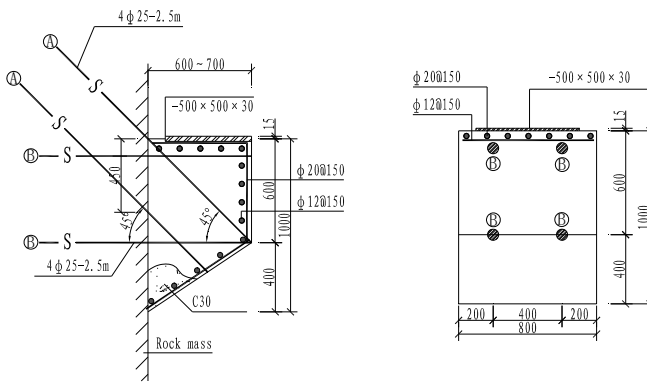
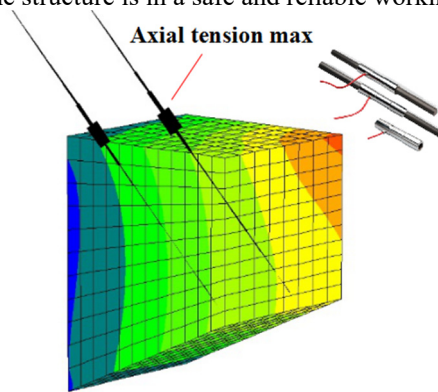


Fig. 9. Trend of maximum tensile force inside bearing rock bolt

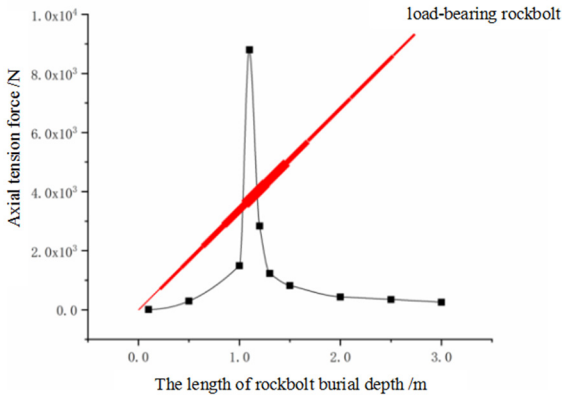
4.2 Analysis of Key Construction Monitoring Results

The integrated stress monitoring rock bolt is selected as diagonal rock bolt, which takes into account the main bearing and component monitoring functions. The deformation and cracking of concrete abutments are obtained through embedded strain gauges. The location of monitoring points and monitoring results are shown in Figure 10. The stress monitoring values of inclined bearing intelligent rock bolt tend to stabilize after 3 days of pouring concrete abutments, and show tensile stress internally. The reading of concrete strain gauge tends to be stable after 7 days of abutments pouring, and the internal strain is mainly compressive strain. After 28 days of the straight-arm rock anchor abutments pouring and curing, under the load of 25 t design crane, the maximum tension inside inclined bearing rock bolt is 5.39 kN and 5.54 kN respectively. The maximum

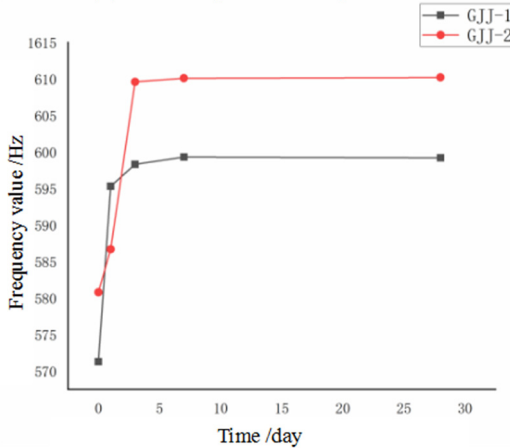
compressive strains inside the concrete are $68.3 \mu\epsilon$, $36.3 \mu\epsilon$, $40.4 \mu\epsilon$ and $41.8 \mu\epsilon$, respectively, which are far less than specification requirements and allowable values of material properties, and the structure is in a safe and reliable working state.



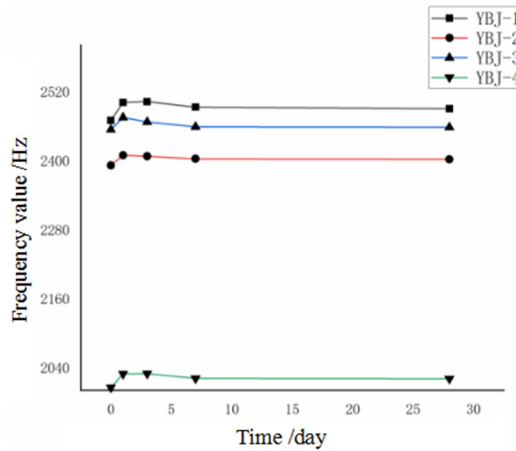
(a) Location of monitoring points



(b) Burial depth of bearing rock bolt



(c) Stress monitoring results

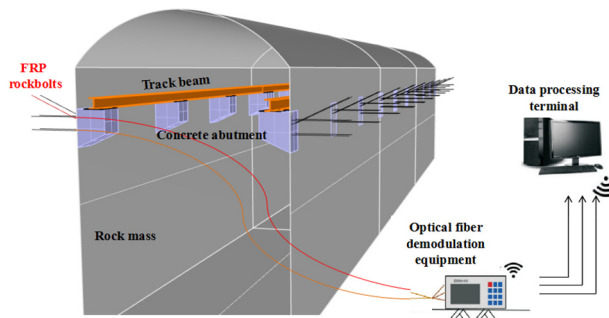


(d) Strain monitoring results

Fig. 10. Analysis of engineering monitoring data

4.3 Feasibility Study of Self Sensing Rock Bolt Monitoring

With the rapid development of anchoring system monitoring technology, underground engineering monitoring systems based on self sensing FRP rock bolt have been successfully applied in major projects such as the Guangzhou Shantou high-speed railway^[17-20]. The embedded fiber optic FRP self sensing rock bolt has a certain bearing performance and can achieve quasi distributed monitoring of axial stress, which is expected to provide a new solution for long-term health monitoring of straight-arm rock anchor abutments structures, as shown in Figure 11.

**Fig. 11.** Intelligent monitoring system for rock anchor abutments structure

The finite difference numerical simulation method was used to analyze the alternative solution of FRP intelligent rock bolt. The material parameter values are shown in Table 5, and the structural response calculation results are shown in Table 6. The introduction of equal diameter FRP intelligent rock bolt as bearing components has not

changed the stress and strain distribution inside straight-arm rock anchor abutments structure, but the peak value has increased. This is beneficial for maximizing the material performance reserves of each component while ensuring structural safety and reliability. In addition, the self perceived FRP rock bolt effectively controls the overall displacement of structure as a bearing component, increases the compression area on the contact surface, and further improves the overall stability of structure.

Table 5. Parameter values of FRP self sensing rock bolt

Diameter	25 mm
Cross sectional area	452 mm ²
Elastic modulus	40 GPa
Ultimate tensile strength	750 MPa
Breaking elongation	2.5%

Table 6. Statistical table of self-sensing rock bolt calculation results

Working condition	Con-1	Con-2	Con-3
Fmax/N	1.024e5	1.475e5	1.052e5
Smax/Pa	5.71e5	7.91e5	8.47e5
Smin/Pa	1.08e6	1.30e6	1.82e6
DispMag/m	5.27e-4	1.09e-3	1.99e-3
Interface-ShearStress/Pa	3.40e5	6.66e5	3.93e5
Compression section ratio ξ	0.80	0.85	0.93

5 Conclusions and Prospects

Based on the construction project of an underground powerhouse, this paper focuses on the problem of instability of straight-arm concrete abutments and rock wall, and obtains the following understanding.

1. Based on the assumption of elastic rock foundation, the limit displacement method is used to carry out selection and design of straight-arm rock anchor abutments, which is in line with the actual bearing failure process of structure. In particular, the new design idea of introducing horizontal auxiliary rock bolt group not only improves overall stability of abutment structure, but also provides a design basis for the selection of neutral point O of contact surface.

2. The bonding performance of contact surface directly determines timing of detachment between rock mass and concrete abutment, and the selection and arrangement of bearing rock bolts are key control factors for the structural bearing limit. As the additional load on the upper part increases, the structural failure exhibits a progressive evolution law of contact surface strength failure, yield of load-bearing anchor rods, and instability of elastic rock foundation.

3. The monitoring results of engineering examples show that the use of integrated stress monitoring rock bolts can achieve the expected effects of structural bearing and health monitoring. The maximum monitored axial force of bearing rock bolt under

designed load is only 5.54kN, far below the allowable values of standard design and material performance. The key bearing components of structure are in a reliable service state.

4. Introducing FRP intelligent monitoring rock bolt as the main bearing components can increase the compression section ratio of contact surface to over 0.8. FRP intelligent rock bolt can achieve full length quasi distributed sensing of axial stress, and the design technology route is feasible. It is one of the effective ways to carry out full life cycle health monitoring of straight-arm rock anchor abutments in the future.

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