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Research on highly-weathered swelling granite roadway support technology

Granite can be easily weathered and often gets disintegrated and argillated when wet. In this paper, we take the granite roadway support work as the research object. Through analysis by X-ray diffraction and scanning electron microscope (SEM), we find that granite contains a great amount of montmorillonite, which is a hydrophilic mineral, and that the rock mass will be rapidly disintegrated when absorbing water. We use the 3D non-linear finite element method to build an elasto-plastic numerical calculation model for the granite roadway, analyze the shotcreting-bolting support schemes with different support parameters, optimize the technical parameters of shotcreting-bolting support from the stress state of the surrounding rock, roadway safety factor and distribution of rock plastic zones, and recommend reinforcing the roadway with 1.8m anchor bolts with spacing of 1.0m × 1.0m and shotcrete with a thickness of 5cm. At the same time, the support monitoring data show that the deformation of the roadway can be clearly divided into three stages - roadway excavation impact, deformation control and stable deformation stages. For a weathered roadway that can be easily disintegrated, it will take the support structure about 3 months to be stabilized. By that time, the anchor bolts and concrete will coordinate well with the deformation of the surrounding rock and have good supporting effects.

Keywords: *Granite; disintegration; argillization; shotcreting-bolting support; monitoring*

Introduction

Soft rock roadway support has always been an important subject for rock mechanics researchers [1-3]. Engineering soft rock is featured with weak cementation, easy weathering and poor self-stabilizing ability and prone to disintegration and argillization when wet [4]. After the excavation of a soft rock roadway, the surrounding rock is in full contact with the outside environment, reducing the strength of the rock mass and rapidly causing its disintegration. As a result, the roadway roof and floor suffers great deformation and will even collapse, causing great economic losses to mine production.

Regarding how to control the stability of the surrounding rock of the soft rock roadway, scholars have done a lot of useful researches, and put forward some theories and technologies [5-7]. Fenner proposed the elasto-plastic analysis method for deformation of surrounding rock, and Kastner modified this method, and gave the Kastner's solution for the elastic-plastic analysis of the surrounding rock. For a long period of time, Kastner's elasto-plastic solution has played an important role in roadway support. However, the drawbacks of Fenner's and Kastner's methods are that they assume after the surrounding rock of the roadway is damaged, it will still maintain its original strength, and as a result, the theoretical calculation range for the surrounding rock elasto-plastic zone is relatively small, and the roadway support designed based on these theories is hard to support the surrounding rock load and can easily cause support failure. Meng et al., (2012) and Liu et al., (2013) analyzed the soft rock roadway failure mechanism according to the mineral composition analysis and geomechanical test. The softening of the surrounding rock when wet, the strong expansion and irrational support forms are the main reasons for roadway damages. In order to solve the difficult problems in soft rock roadway support, based on the physical and mechanical properties of the surrounding rock and rock stress measurement, Wang et al., (2013) proposed a bolt-net-anchor coupling support scheme by optimizing supporting parameters.

To sum up, scholars from home and abroad have conducted detailed researches on the failure mechanism, supporting theories and supporting technologies of soft rock roadway, but the problem that the weathered swelling surrounding rock is argillated when wet has not yet been effectively solved. Therefore, the highly-weathered swelling soft rock roadway support is still a difficult and urgent problem in underground mine construction. This research takes the soft rock roadway in Lancang as the object and studies the highly-weathered swelling granite roadway support technologies through indoor test, numerical simulation and on-the-spot monitoring.

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2. Project profile

Tangziao is located in Gejiu City, Yunnan Province. The geologic structure of the mine area is complex, with north-south and east-west fault developments. There is a large amount of granite in the contact zone between the ore body and the surrounding rock. The rock mass has high strength when being excavated, and blasting is usually required, so the roof rock mass is often damaged to different extents. However, when the surrounding rock is exposed to wet air, it will be rapidly weathered and disintegrated, sometimes leading to roof falls. Under the effect of water, it can be weathered or disintegrated very fast, and it can be softened into mud as soon as in 30 minutes. After roadway excavation, the floor will be bulged and deformed to varying extents, with a maximum swelling amount of 20~30cm, and the sides will also be shrunk and deformed. A highly weathered granite roadway needs to be treated or repaired every 3-5 months.

After repeated repairs, the sides will suffer from more serious shrinkage and deformation, and the roof will sink, resulting in loss of roadway stability. The roadway supports used by enterprises are usually made of wood. Traditional wood support structure can support the roadway very fast but is of low strength and prone to damages and needs frequent replacement. After the granite is argillated, in particular, this kind of support can work longer. Exploring the instability mechanism of highly weathered granite roadway instability and improving the existing roadway support technologies are of great importance to ensuring mine work safety.

2. Microstructure of the granite

Considering the zoning characteristics of the rock mass and the intended purposes of the roadway, we have carried out an engineering geological survey on the 1650 mid-section and the 1700 mid-section of the auxiliary shaft and the 1675 and 1800 mid-sections of the main shaft, with a total length of about 500m. The results show that the surrounding rock of the roadway is mainly composed of granites with different degrees of weathering, mixed with some marble, and the lithology is complicated. The fault structure in the mine area is developed. The surrounding rock on both sides of the roadway is extremely broken as a result of fault activities, and due to the water conductivity of the fault, the granite is seriously argillated and swelling. Through X-ray diffraction analysis of rock samples, we obtain the composition of the rock, as shown in Fig.1. The minerals in this granite mainly include montmorillonite, kaolinite, chlorite, rectorite and so on, whose contents are shown in Table 1.

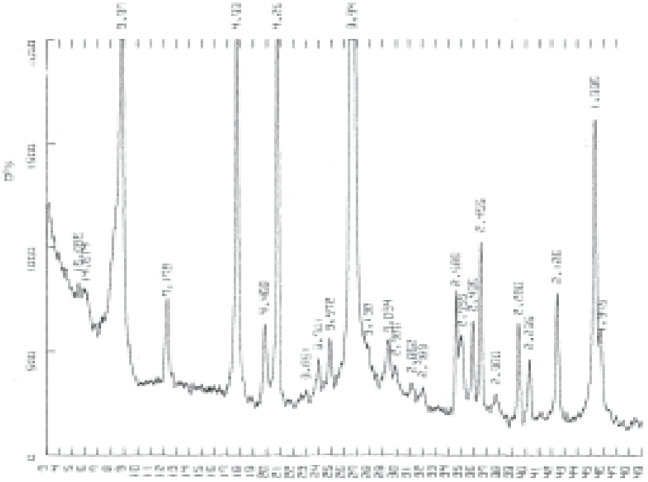


Fig. 1 Granite X-ray diffraction spectrum

The microstructure of the rock is a geological and historical product and contains a trace of various geological effects, so it has complex structural features. In the long-term engineering practice, it is found that the macroscopic mechanical properties of the rock are controlled by its micro-structural characteristics. Any continuum model based on moderate homogenization is difficult to accurately describe the complexity of the structure or reflect the diversity and uncertainty of the microstructure of the rock mass. We observe the microstructures of tuff in natural state by doing scanning electron microscopy (SEM) of the rock samples, as shown in Fig.2. From this figure, we can see that the rock is strongly altered and the mineral composition and structure of the original rock are unrecognizable. Altered minerals mainly include microaphanitic kaolinite, illite, iron mud, a small amount of quartz and a large amount of metal minerals. In local parts, kaolinite alternates with iron mud in irregular stripes, forming a pseudofluidal structure.

3. Physical and mechanical properties of granite

3.1 Swelling characteristics of granite

We performed a free swell test on the granite samples collected on site according to the Standard for Soil Test Method GB/T 50123-1999 and the results are shown in Table 2. According to the results, free swelling ratio of granite

Table 1: Expansive clay mineral components of granite and the contents thereof

Sample no.	Montmorillonite (%)	Kaolinite (%)	Chlorite (%)	Rectorite (%)	Total content of swelling minerals (%)
1	13~27	13~27	-	12~20	>38
2	15~25	5~12	-	8~14	>28
3	18~26	5~12	-	6~10	>29
4	20~30	12~24	5~12	5~12	>42

TABLE 2: FREE SWELL TEST RESULTS OF TUFF

Sample no.	Weight (g)	Volume (ml)	Volume reading at different time (ml)			Free swell ratio (%)
			2h	4h	6h	
1	10.86	10.0	12.1	12.1	12.2	22.0
2	11.79	10.0	12.5	12.5	12.5	25.0
3	11.81	10.0	13.0	12.9	12.8	28.0
4	10.82	10.0	11.9	11.8	11.8	18.0

TABLE 3: FREE SWELLING RATIOS OF TUFFS WITH DIFFERENT CLAY MINERAL GRAIN SIZES

Mineral grain size (mm)	No.	Sample weight (g)	Initial volume (ml)	Test volume (ml)	Free swell ratio (%)
1~2	1	13.5	10.0	11.6	16.0
	2	14.2	10.0	11.4	14.0
0.5~1	3	14.1	10.0	12.7	27.0
	4	14.3	10.0	12.8	28.0

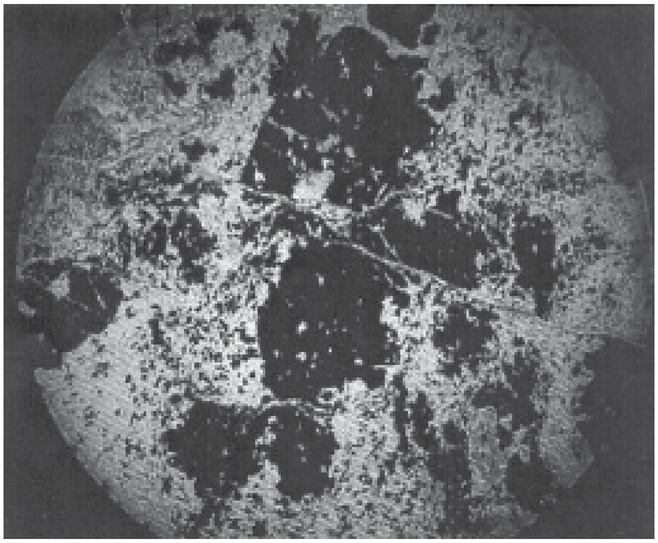


Fig.2 Granite microstructure

in Tangziao is 23.25%, and the content of the swelling clay mineral montmorillonite is greater than 25%. According to the grading standards for swelling soft rock, granite in Tangziao is strongly swelling soft rock.

We designed the free swell tests on rock with different grain sizes, and the results are shown in Table 3. From Table 3, we can see that the free swelling ratio of the swelling soft rock is inversely proportional to the grain size of the clay mineral, and it is greatly affected by the grain size of the clay mineral. The main reason is: for rock samples with small clay mineral grain sizes, the surface area is large, and thus it can fully react with the water; for rock samples with large clay mineral grain sizes, there are large gaps inside and after the rock reacts with the water, some swelling amount fills some of the gaps and the rest of the swelling amount shows the change in the sample volume.

The argillization of the swelling rock is the process of water absorption and disintegration when the rock is wet. It reflects the interaction between rock and water. Fig.3 shows the test records of tuff at different times of its disintegration and argillization after being wet. By analyzing the swelling tuff argillization process, we can divide the process into three stages. (1) After immersing the tuff in the water, the surface particles of the rock body first adsorbs water molecules to form a water film, and some of the cementation material is dissolved in water. Water enters the rock mass along the discontinuous fractures and the body is disintegrated into small pieces. This period generally lasts 3~5min. (2) water goes deeper into the rock along the cracks and the clay minerals in the body continue to collapse. The small pieces are gravel-like rock. This period lasts 10min. (3)

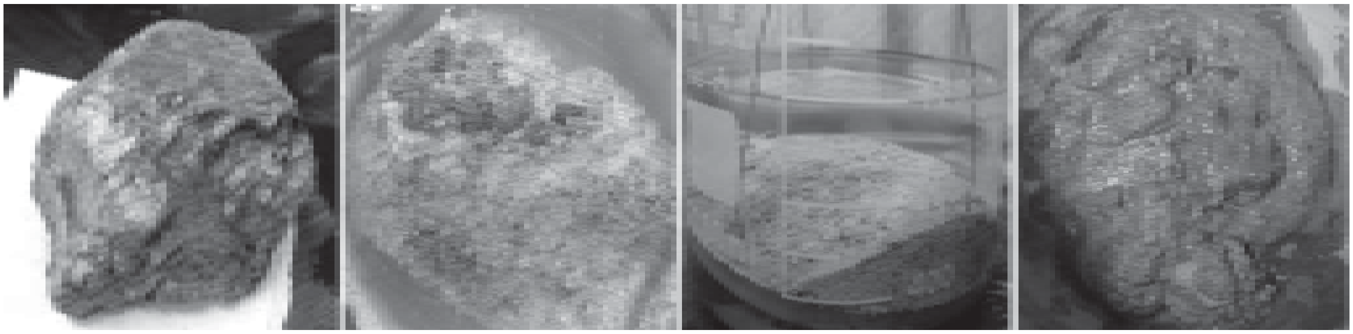


Fig.3 Disintegration of wet tuff at different times

With the dissolution of the cementing material in the rock mass, the granular material becomes mud-like. This period lasts for 2h.

3.2 Rock mechanical test on soft-rock roadway

Rock mechanics parameters of roadway surrounding rock are the key to roadway support design. There are mainly marble and granite in the surrounding rock of Tangziao. Field investigation shows that though marble has developed joint fissures and is of massive or cataclastic structure, it will not be argillated or swelling. Therefore, a marble roadway generally does not require support, and shotcrete is only needed to keep it stabilized; in areas with serious cracking, shot anchoring net support is generally adopted. Strongly swelling granite is a kind of soft rock, and the weathering degree of such rock has a great impact on the stability of roadway, so we perform rock mechanical tests on rocks with different weathering degrees. The mechanical test results of marble and granite with different degrees of weathering are shown in Table 4.

4. Analysis of instability mechanism and countermeasures with granite

There are many complicated reasons that lead to the deformation and damages of a granite roadway. Through the swell test and argillization test on granite and the field survey on the deformation of surrounding rock, we find there are four factors that can lead to the instability and damages of a granite roadway.

(1) The swelling clay mineral contained in the granite plays a decisive role in the deformation and damages of a roadway. It is the internal factor. Due to the swelling clay mineral contained in the granite, the granite reacts strongly with the water, making the granite strongly swelling and argillated.

(2) The ground stress and status of the granite roadway has a controlling effect on the failure mechanism of the granite. It is the external factor. Before the roadway is excavated, the joint fissures of the rock are closed. But after the excavation, due to the bias pressure and affected by the dynamic loads like blasting vibration, the joint fissures of the rock become larger and deeper, and the broken rock zone of the surrounding rock is enlarged. With the enlargement of the broken rock zone, the stability of the surrounding rock will be reduced and at last, it may collapse.

(3) Changes in the physical environment where the roadway is located play a catalytic role in the deformation of the granite. Changes in the physical environment mainly include those changes in humidity and initial pressure. The swell test shows that the change in the ambient humidity has a great impact on the water-physical properties of the ore-bearing rock, especially on swelling.

(4) The support form and strength adopted are important to controlling the size of the loose zone and stability of the granite roadway. The stability of a roadway depends on the range of the stable area in the surrounding rock of roadway. Therefore, the support form, measures and materials are essential.

Based on the above analysis, in order to maintain the roadway stability, certain engineering measures must be taken to reduce the range the swelling/deformed failure area and surrounding displacement of roadway, mainly including the reducing the activation of swelling rock, increasing the strength of the rock body and reducing the two dimensional stress of the rock body. Specific countermeasures are as follows:

(1) Use smooth blasting technologies to reduce the generation of faint cracks; after blasting, immediately conduct shotcrete to reinforce the surrounding rock, form a closed loop, and avoid alternation of air wetting and drying to minimize the water absorption by swelling rock. Strengthen the drainage works of the roadway to prevent the granite from being immersed in water and reduce swelling.

(2) Apply anchor bolts and anchor cables to increase the shear and tensile strength of the swelling rock body. Grouting can help improve the compression, tensile and shear strengths of the rock body.

(3) Take such support measures as U-shaped supports, cast concrete and anchor bolts to reduce the bias stress and two dimensional stress created in the roadway excavation.

Table 4: Mechanical parameters of roadway surrounding rock

Rock name	Gravity (kN/m)	Compressive strength (MPa)	Tensile strength (MPa)	Elasticity modulus (GPa)	Shear strength	
					Cohesion /MPa	Internal friction angle (°)
Highly-eathered granite	23.37	-	-	-	0.199	26.23
Weakly-athered granite	25.74	82.94	4.27	29.076	3.423	34.12
Granite	25.82	140.21	6.405	29.076	4.837	40.76
Marble	26.89	33.38	1.42	20.375	4.051	50.37

5. Study on the granite roadway support technologies

In order to study the deformation rule of the weathered swelling granite roadway and the optimization of roadway support technical parameters, we use a 3D non-linear finite element programme 3D-σ to build an elastoplastic numerical model for granite roadway to perform a numerical simulation of the soft rock roadway construction process.

We analyze the change features of the elasto-plastic zone, stress distribution and roadway surface deformation in the surrounding rock of the excavated roadway without being supported, and at the same time study the control effects of different support parameters on the roadway stability to find out the suitable support scheme.

5.1 Support technologies and simulation plan

According to the mechanical properties of the weathered swelling granite, the roadway uses shotcreting-bolting support. The advantages of this technology are that after the surrounding rock is blasted, concrete will be sprayed in a timely manner to reduce the exposure time of the rock body; anchor bolts can change the stress state of the surrounding rock and improve the stability of the surrounding rock. In the numerical simulation, we consider the impacts of different lengths of anchor bolts, spacing and thicknesses of shotcrete on the roadway stability so that we can select the optimal and most cost-effective anchor bolt length, spacing and shotcrete thickness. Due to the constraints of onsite construction conditions, the lengths of the anchor bolts are 1.5m and 1.8m, the spacing between anchor bolts is 0.75m×0.75m, 0.75m×1.0m and 0.75m×1.2m and the radius of the anchor bolt is 0.02m. General cartridge bolts are used for the roof and two sides of the roadway, with an elasticity modulus of 95GPa, and the high-strength bolts are used for the floor with an elasticity modulus of 200GPa. There are a total of 8 simulation schemes, whose specific parameters are shown in Table 5.

Table 5: Design scheme for shotcreting-bolting support parameters

Scheme no.	Anchor bolt length /m	Concrete thickness /cm	Spacing between anchor bolts /m
1	1.5	5	0.5×0.5
2	1.5	10	0.5×0.5
3	1.8	5	0.5×0.5
4	1.8	10	0.5×0.5
5	1.5	5	1.0×1.0
6	1.5	10	1.0×1.0
7	1.8	5	1.0×1.0
8	1.8	10	1.0×1.0

5.2 Modelling

According to the elasto-plastic mechanics, after a round hole is drilled in an infinite elastic body under uniform load, the stress state around the hole will change significantly. The influence of this change is only limited to the nearby local area. In the area at a radius 3 times the hole diameter, the stress is 11% greater than that before the hole is drilled. At a radius 5 times the hole diameter, the relative difference in stress is less than 5%, which is negligible in engineering. In this case, the area at a radius 3~5 times the hole diameter can be used as the computational domain in the calculation of the finite element. According to the cross-section area of Tangziao mine roadway and the results of computational domain analysis, we build a 3D finite element numerical model. The model size is 50m×65m×60m, that is, 50m (in the z direction) along the roadway direction, 65m (in the x direction) in the direction vertical to the roadway and 60m (in the y direction) in the perpendicular direction. There are a total of 81380 nodes in the roadway model. The grid division is shown in Fig.4 and the computer simulated roadway diagram is shown in Fig.5. The physical and mechanical parameters of the rock formation and the supporting structure are shown in Table 6.

The following simplifications and assumptions are made in the simulation: (a) the surrounding rock is regarded as isotropic. The rock stratum is assumed to be made of elastic-perfectly plastic material. And the failure of the rock mass

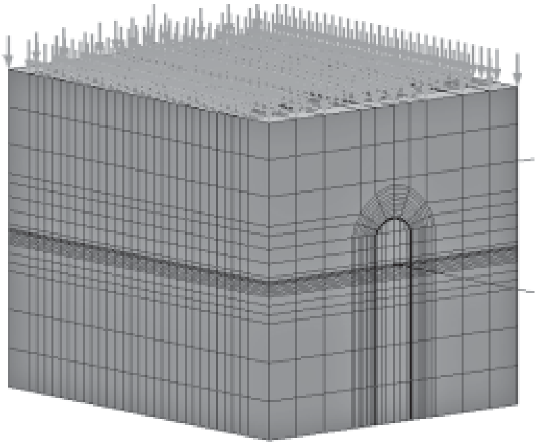


Fig.4 3D finite element computer model

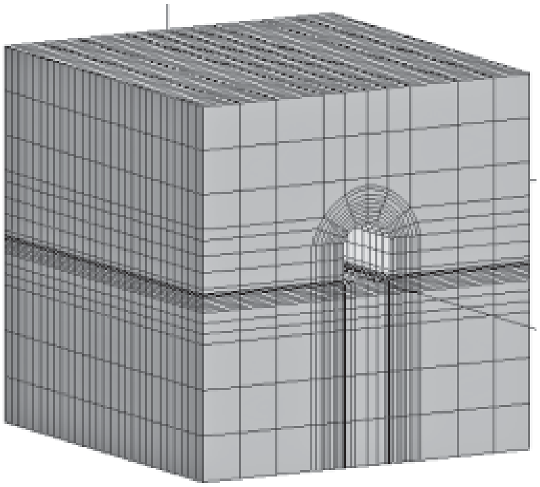


Fig.5 Computer simulated roadway excavation

Table 6: Mechanical calculation parameters of modeling materials

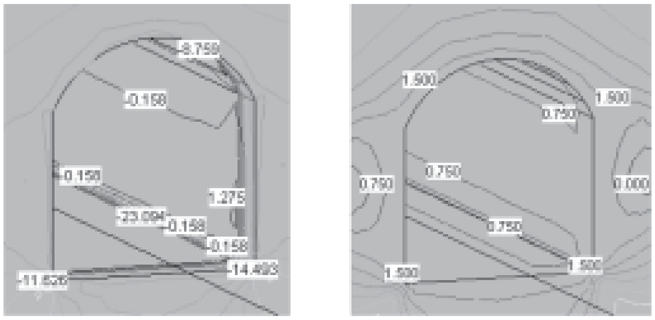
Rock name	Density ($g.cm^{-3}$)	Elasticity modulus (GPa)	Poisson's ratio	Tensile strength (MPa)	Cohesion (MPa)	Internal friction angle (°)
Marble	2.7	20	0.30	4.7	3.8	37
Granite	2.3	29	0.32	1.8	4.6	40
C30 concrete	2.2	2.1	0.17	4.8	4.0	40
Anchor bolt	7.85	2.5	0.20	-	-	-

obeys the Drucker-Prager plastic failure rule; (b) an ideal linear elastic constitutive model is used for the anchor bolt and concrete support materials; (c) external force is applied to the support structure to achieve the granite swelling; (d) no measured data are available for the in-situ stress. In the calculation, the lateral pressure coefficient is 1.15.

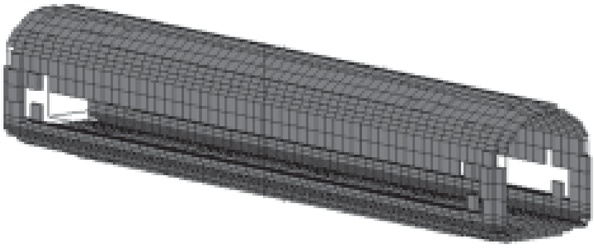
5.3 Analysis of numerical simulation results

5.3.1 Initial roadway excavation results

In the case where the roadway is not supported after being excavated, the calculation results are shown in Fig.6. In the figure, “-” indicates that the stress is compressive stress. The calculation results show that the surrounding rock in the roof and below the waistlines on two sides of the roadway are seriously damaged, and the stress is mainly concentrated on the borders between the floor and the two sides. The maximum compressive stress is -25.792MPa, the minimum safety factor of the roadway is 0.75, and the whole elasto-plastic zone is obvious. Therefore, after being excavated, the roadway cannot maintain its stability well and it is necessary to reinforce it.



(a) maximum principal stress (b) safety factors



(c) Distribution of the elasto-plastic zone

Fig.6 Analysis results of initial roadway excavation

5.3.2 Comprehensive analysis on the support schemes

Computation results of the unsupported roadway shows that without support, the roadway cannot maintain its stability. According to the shotcreting-bolting support construction process, we first reinforce the roof and the two sides with anchor bolts, steel wire mesh and shotcrete. There are four simulation schemes in this paper and we only provide Scheme 1 here, shown in Figs.7 and 8.

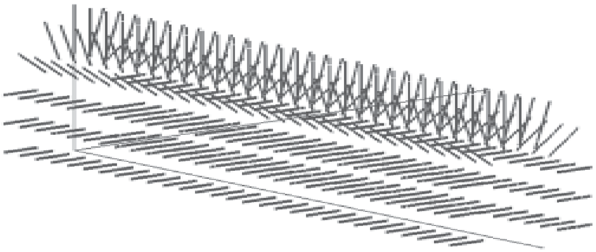


Fig.7 Anchor bolt support reinforced model

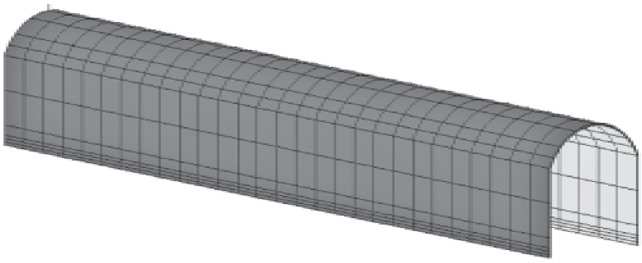
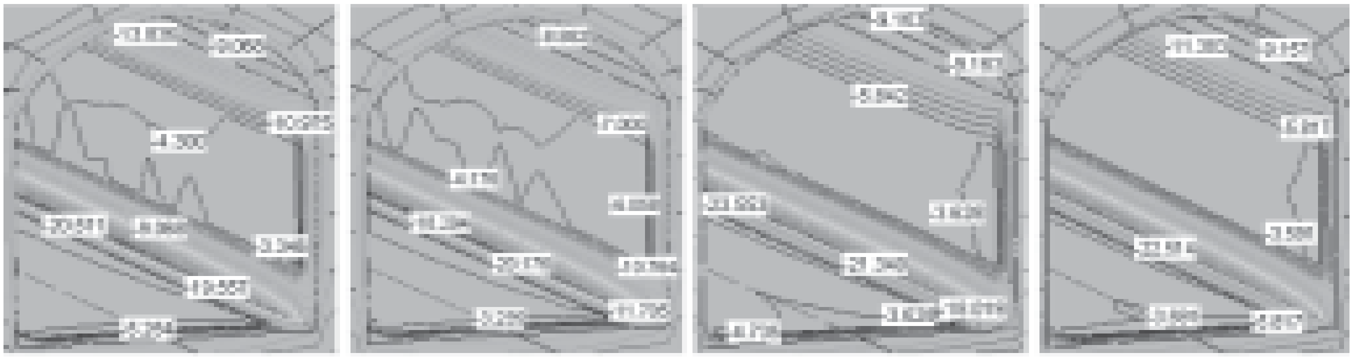


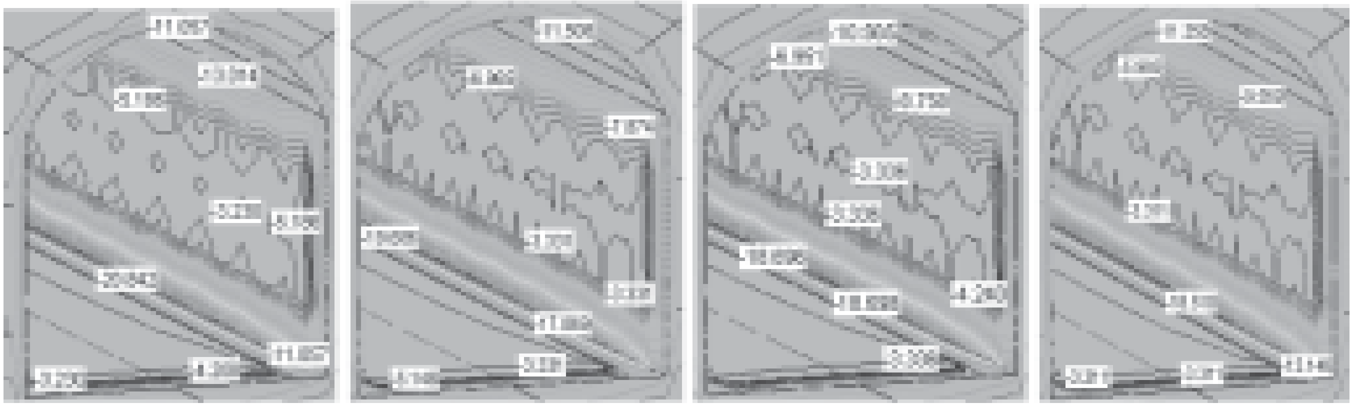
Fig.8 Shotcrete support model

(1) Comparison of surrounding rock stresses

The stress analysis results of the surrounding rock are shown in Fig.9. The simulation results show that the anchor bolts have significantly improved the stress state of the surrounding rock, with obvious suspension extrusion effects. The maximum compressive stress in the eight support schemes is -23.553 MPa and the minimum is -18.698 MPa, with a difference of nearly 5 MPa. With the same spacing and shotcrete thickness, the stress of the surrounding rock when the bolt length is 1.8 m is less than that when the bolt length is 1.5 m. And the spacing between anchor bolts has a small impact on the roadway stability, so based on the stress analysis and from the perspective of cost effectiveness, using 1.8m-long anchor bolts and spacing 1.0m×1.0m can meet the support needs. Now we compare the effects brought by different thicknesses of shotcrete. In Scheme 2, 4, 6 and 8, the concrete is 10cm thick while that in others is 5cm thick. Although it can improve the stress to some extent, the



(a) Scheme 1 (b) Scheme 2 (c) Scheme 3 (d) Scheme 4



(e) Scheme 5 (f) Scheme 6 (g) Scheme 7 (g) Scheme 8

Fig.9 Surrounding rock stresses under different support schemes

change is too small, so a concrete thickness of 5cm will be able to control the deformation of the floor.

(2) Comparison of roadway safety factors

The computation results of roadway safety factors under different support schemes are shown in Fig.10. The analysis results show that with the same length of anchor bolt, the roadway safety factor when the shotcrete is 10cm thick is higher than that when the shotcrete is 5cm thick. With the anchor bolt length and shotcrete thickness, the spacing between anchor bolts is directly related to the roadway safety factor. The greater the spacing is, the lower the safety factor will be; otherwise, the higher it will be. After the roadway is reinforced, the safety factor under all schemes is higher than the critical value 1.0, but from the perspective of safety, the safety factor should be as high as possible. So in order to meet the safety requirements and save costs, we suggest using 1.8m-long anchor bolts with spacing of 1.0m × 1.0m together with shotcrete to reinforce the roadway.

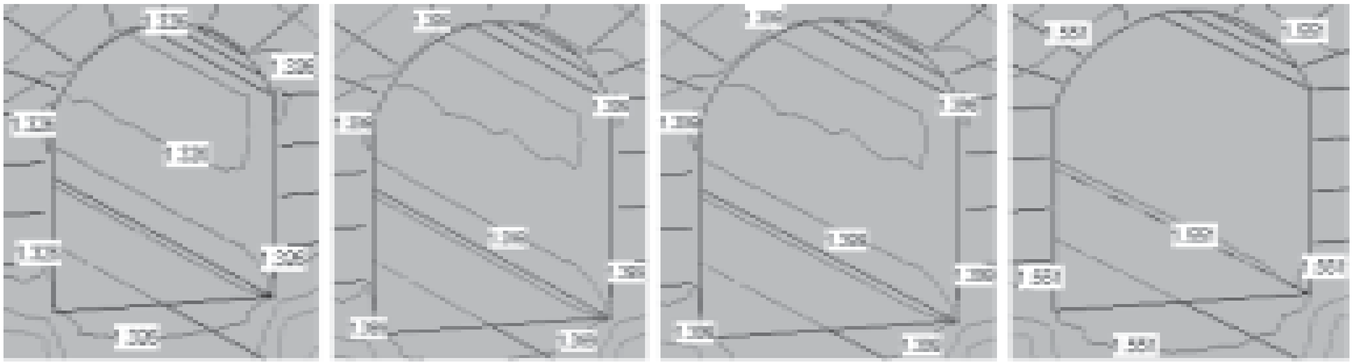
(3) Comparison of elasto-plastic zone distribution in the surrounding rock

The distribution of elasto-plastic zones in the surrounding rock under different support schemes is shown in Fig.11. Comparison results show that except that there are certain elasto-plastic zones in the lower parts on the two sides of the roadway under Scheme 1, there is hardly any other under schemes (except some in local parts), so it is difficult to tell which one is better.

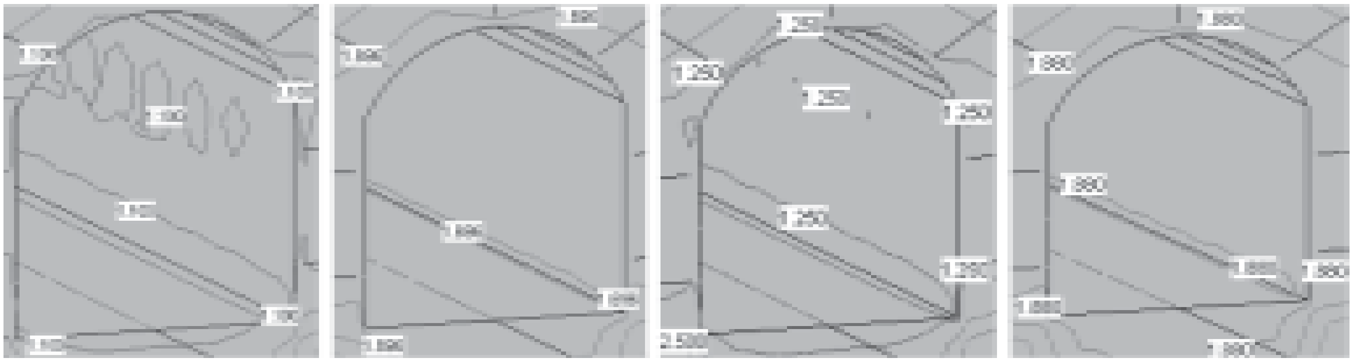
6 Roadway deformation and anchor bolt stress monitoring and analysis

6.1 Monitoring on the convergence and deformation of the roadway surrounding rock

In order to determine the convergences of the surrounding rock surface in the horizontal and vertical directions and the convergence rates to assess the stability of the surrounding rock, we should first determine the absolute displacement of the surrounding rock surface. We use the JSS30A digital convergence gauge and homemade nut hook in monitoring. As shown in Fig.12, the deformation of the roadway can be clearly divided into three stages - roadway excavation impact, deformation control and stable deformation stages. The roadway excavation will lead to the redistribution of surrounding rock stresses and the elastic deformation of the surrounding rock can be promptly released, which can be seen in the initial rapid deformation of the surrounding rock. With the working face continuing to advance, the shotcreting-bolting support structure gradually shows its effects and the secondary stress field is gradually



(a) Scheme 1 (b) Scheme 2 (c) Scheme 3 (d) Scheme 4



(e) Scheme 5 (f) Scheme 6 (g) Scheme 7 (g) Scheme 8

Fig.10 Roadway safety factors under different support schemes

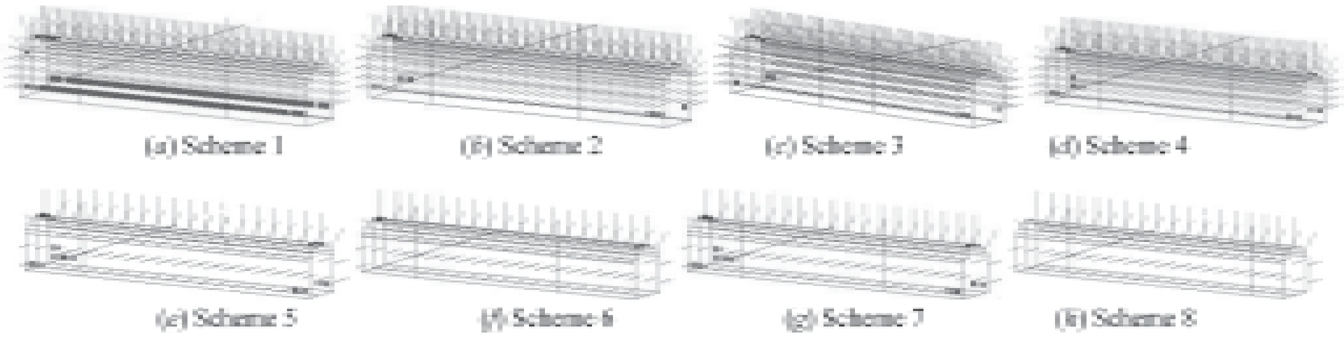


Fig.11 Distribution of elasto-plastic zones in the surrounding rock under different support schemes

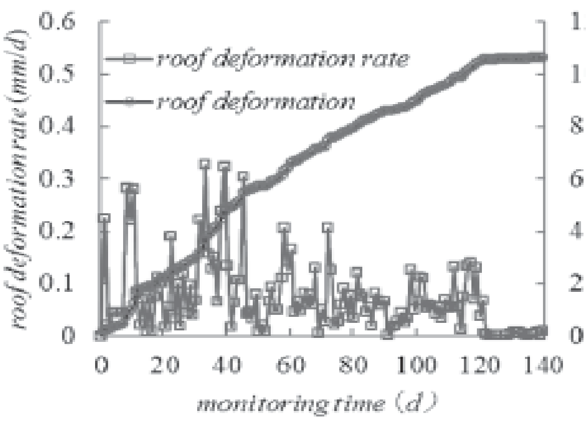


Fig.12 Roof deformation tendency chart

formed. At this time, the roadway is in a stress balance, which is shown in the slower deformation rate and the gradual convergence of the roadway. From the deformation curve of the surrounding rock with the time, we can see that after the roadway is excavated for about 100 days, the deformation of the roadway surrounding rock starts to stabilize, at a deformation rate of less than 0.1mm/d.

6.2 Monitoring on the anchor bolt stress

We use the MCS-400 rock-bolt dynamometer to measure the stress of the anchor bolts in the roadway, and the results are shown in Fig.13. From the stress curve measured by the dynamometer, we can see that in the initial stage of the support structure, the elastic deformation of the surrounding rock is rapidly released, causing great stress on the bolts.

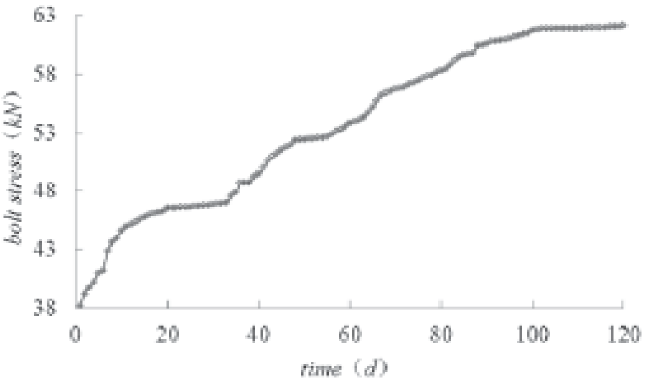


Fig.13 Anchor bolt stress monitoring data curve

Especially under the construction disturbance, the anchor bolt stress fluctuates significantly. After about 3 months, the anchor bolt stress starts to stabilize. This indicates that the anchor bolts and the concrete coordinate well with the deformation of the surrounding rock, showing good supporting effects.

7. Conclusions

(1) Granite can be easily weathered and often gets disintegrated and argillated when wet. It has low strength and can only remain stable in a short while. As granite contains large amounts of hydrophilic minerals like montmorillonite and illite, in the roadway excavation, disasters often occurs, including roof falls, floor bulges and deformation of two sides.

(2) We use the 3D non-linear finite element method to build an elasto-plastic numerical calculation model for the granite roadway, optimize the technical parameters of shotcreting-bolting support from the stress state of the surrounding rock, roadway safety factor and distribution of rock plastic zones, and recommend reinforcing the roadway with 1.8m anchor bolts with spacing of 1.0m × 1.0m and shotcrete with a thickness of 5cm.

(3) Onsite monitoring data show that the deformation of the roadway can be clearly divided into three stages - roadway excavation impact, deformation control and stable deformation stages. For a weathered roadway that can be easily disintegrated, it will take the support structure about 3 months to be stabilized. By that time, the anchor bolts and concrete will coordinate well with the deformation of the surrounding rock and have good supporting effects.

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