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Research on Grouting Parameters of "Expansion-Grouting" Anchoring Technology for Soft Rock Roadway Floor Anchor Cables

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ABSTRACT

The "expansion–injection" anchoring technology of anchor cables in the bottom plate of soft rock roadways can not only give full play to the advantages of expansion anchoring to improve the anchoring effect of anchor cables in soft rock roadways, but also enhance the bearing capacity of the injected rock mass through grouting, thereby optimizing the stress distribution of the bottom plate and reducing the damage of the surrounding rock caused by tensile stress. Since the selection of grouting process parameters will directly affect the diffusion range and penetration effect of the grout, and the selection of grouting process parameters is often determined by experience and lacks scientific basis, this study uses numerical simulation to explore the influence of common grouting parameters such as grouting pressure, grouting time and the spacing of grouting anchor cables on the diffusion range of the grout. In order to provide a scientific basis for optimizing the design of roadway support. The numerical analysis results show that the grout diffusion radius increases nonlinearly with the increase of grouting pressure, while the expansion efficiency of the grout diffusion range gradually decreases and tends to be stable with the increase of grouting time. Meanwhile, a larger spacing of grouting anchor cables is not conducive to the formation of the grouting reinforcement area of the base plate. Finally, the reasonable parameter range was determined as the grouting pressure of 3-4 MPa, the grouting time of 8-10 minutes, and the anchor cable spacing of 2.5-3 m.

KEYWORDS

Soft rock roadway; Bottom plate reinforcement; Grouting anchor cable; Parameter optimization.

1. INTRODUCTION

In recent years, with the continuous development of soft rock roadway control technology, scholars at home and abroad have explored a variety of soft rock roadway floor control technologies suitable for different working conditions through extensive practical and theoretical research, such as grouting reinforcement, anchoring support, and floor replacement methods. However, these traditional techniques still have certain limitations. For example, grouting reinforcement technology improves the integrity of the surrounding rock by injecting cement slurry or chemical slurry to fill the fractures of the rock mass. But due to the selection of slurry materials, it is difficult to take into account the setting time, strength and ability of injection[1]. Anchoring support technology uses anchor cables or anchor rods to connect the surrounding rock with relatively hard rock layers or supporting structures to achieve the purpose of reinforcement. However, under soft rock conditions, due to the significant deformation and rheological characteristics of the rock mass, the anchoring force often decays rapidly, and the supporting force is insufficient[2]; The base plate replacement technology is originally designed to enhance the load-bearing capacity and stability of the base plate by replacing the weak base plate with high-strength materials such as concrete. However, its construction is complex, involving a large amount of excavation and backfilling work. The selection of materials and quality assurance pose a huge challenge, often making it difficult to achieve the desired reinforcement effect. To sum up, the single reinforcement technology has limitations such as insufficient adaptability, high construction difficulty, high cost and unstable effect in the reinforcement of the bottom plate of soft rock roadways. It can be seen from this that traditional support measures have become insufficient in dealing with the problem of large deformation of soft rock. There is an urgent need to develop a more efficient, economical and environmentally friendly technology to solve the reinforcement problem of the bottom plate of soft rock roadways. The successful experiences of technologies such as “floor slab anchoring”, “floor slab anchor cable bundle + deep and shallow floor slab grouting”, and “multi-level coupling reinforcement” indicate that the synergistic strategy of active support for roadway floor slabs and modified floor slab rock layer grouting is an effective method for floor slab treatment[3-5].

Combining the support requirements of the bottom plate of soft rock roadways in coal mines and the successful experiences of predecessors, this study proposes an anchoring method for bottom plate anchor cables. This method combines the advantages of anchor cable expansion anchoring and grouting anchor cable support. On the one hand, through the setting of the expansion section, the contact area between the anchor solid and the rock mass is increased, and the anchoring effect is improved. On the other hand, the grouting process can fill the fractures in the rock mass and enhance the integrity and stability of the rock mass. After applying the preload force, the passive support is transformed into active support, which further enhances the anti-slip ability of the anchor cables in soft rock and ensures the support effect of the floor anchor cables in soft rock roadways. Therefore, conducting research on the diffusion law of grout for the bottom plate of soft rock roadways and the grout parameters of the “expansion-injection” anchoring technology for the bottom plate anchor cables will provide theoretical support for the engineering application of this technology and expand new means for the treatment of the bottom plate of soft rock roadways.

2. CONSTRUCTION OF THE NUMERICAL MODEL FOR THE DIFFUSION OF GROUTING LIQUID IN THE BOTTOM PLATE ANCHOR CABLE

COMSOL Multiphysics software is a simulation platform based on the solution of partial differential equations, which is capable of simultaneously describing and solving various physical fields such as mechanics, fluids, heat conduction and chemical reactions. This software supports multi-field coupling simulation and is widely used in fields such as rock mass engineering, electromagnetic fields, acoustic analysis, fluid mechanics, heat and mass transfer, and chemical reactions. Therefore, in this section, COMSOL Multiphysics is used to explore the diffusion law of the grouting liquid for the bottom plate anchor cables.

2.1. Establishment of Geometric models

2.1.1. Basic Assumptions

In order to simplify the numerical calculation process, on the basis of retaining the basic setting of fluid-structure coupling during the grouting process, the following simplifications are made for the grouting slurry and the injected rock mass. The specific assumptions are as follows:

① Ignoring the gravity and time-varying properties of the slurry, it is assumed that the slurry is an incompressible isotropic Newtonian fluid, and there is no segregation phenomenon during the flow of the slurry.

② It is assumed that the surrounding rock of the roadway is an isotropic continuous porous medium, and its constitutive relationship is based on the linear elasticity assumption;

③ The grouting slurry needs to fill the anchoring hole first and then permeate and diffuse outward. The flow and permeation process of the slurry conforms to Darcy's law of fluid mechanics.

④ The study only considers the diffusion of slurry inside the tunnel floor slab. Therefore, it is assumed that the slurry will not seep out from the orifice, and there is no slurry flow on the inner surface of the tunnel and the outer surface of the model.

2.1.2. Model Dimensions and Boundary Conditions

Based on the above basic assumptions and research purposes, the actual geological conditions of the transportation roadway in the 12203 working face of Zhaojiazhai Mine were selected as the simulation object to establish a numerical model. The solid mechanics module and Darcy's law module were coupled using the control equation in COMSOL Multiphysics to explore the law of slurry diffusion under different grouting parameters. The overall size of the model is 30×15×30 m. Among them, the roadway has a trapezoidal cross-section, with a width of 4 m at the top, 5.4 m at the bottom, and a height of 3.4 m. The anchoring hole position of the grouting anchor cable is located at the center of the model roadway. The diameter of the hole is 0.028m and the length is 7m. The wedge-shaped expansion hole setting is achieved through Boolean operation at the bottom of the anchoring hole. To ensure that the numerical calculation results can converge and the calculation process is efficient, the overall mesh division of the model adopts free tetrahedral meshes, and the meshes around the roadway floor and grouting holes are locally densified. A total of 32,082 unit meshes are generated. After testing, the mesh quality is good and meets the convergence requirements. The mesh division situation and the detailed dimensions of the geometric model are shown in Figure 1.

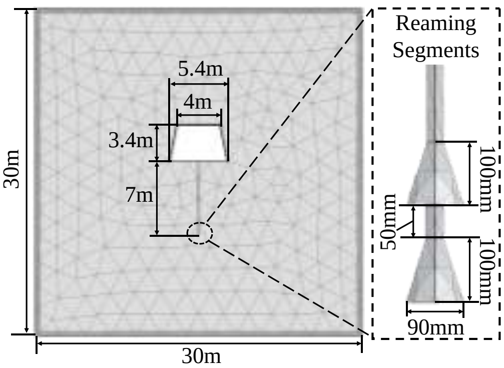


Figure 1. Geometric models and meshing

The upper surface of the model is subjected to a uniformly distributed load with an equivalent vertical stress of 7.25 MPa to reflect the action of the overlying rock layer. The bottom of the model is a fixed constraint, the four boundaries of the model are roller support constraints, and both the outer surface of the model and the inner surface of the roadway are set as flow-free boundaries. While the perimeter of grouting hole is Dieldrin boundary condition, and the slurry injection process is controlled by constant pressure parameter. Furthermore, the model adopts the transient numerical analysis method to iteratively solve the convection-solid coupling process, and achieves the precise simulation of the dynamic process through the control of time step size.

2.2. Simulation Parameter setting

The density and viscosity of the slurry directly determine its flow performance. High viscosity increases resistance and reduces the diffusion range, while a lower density is conducive to fluid migration, but it may have a negative impact on the bearing capacity after curing. Furthermore, when studying the diffusion effect of slurry, it is necessary not only to pay attention to the water-cement ratio of the slurry itself, but also to consider the influence of the physical and mechanical properties of the rock mass on fluid infiltration. The elastic modulus, Poisson's ratio and porosity of rocks not only determine the flow velocity of the slurry within the rocks, but also affect the curing effect of the slurry after diffusion. Therefore, the reasonable selection of the types of grouting materials, the water-cement ratio, and the matching of physical parameters of the rock mass are crucial for improving the grouting diffusion effect and the final reinforcement effect. To ensure the authenticity and feasibility of the simulation, the model parameters are set in combination with the parameter designs in relevant literatures and the actual geological conditions of the transport roadway in the 12203 working face. The relevant parameters are detailed in Table 1[6,7].

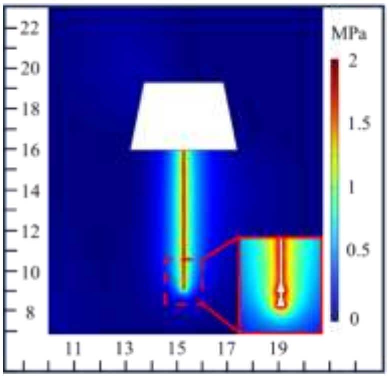
Table 1. Model-related parameters

The name of the parameter	**Detailed values**
Elastic modulus	3.8×1010 Pa
Poisson's ratio	0.25
Slurry density	1650 kg·m-3
Slurry viscosity	162 MPa·s
Initial permeability	4.5×10-12 m2
Porosity	0.13

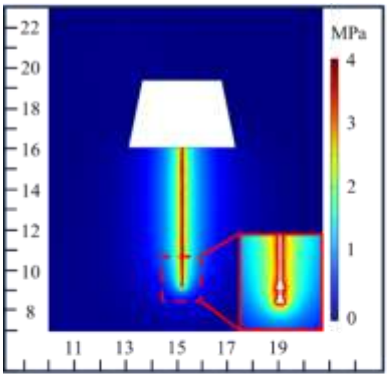
3. ANALYSIS OF THE GROUT DIFFUSION LAW OF THE BOTTOM PLATE GROUTING ANCHOR CABLE

3.1. The influence of grouting pressure on grout diffusion

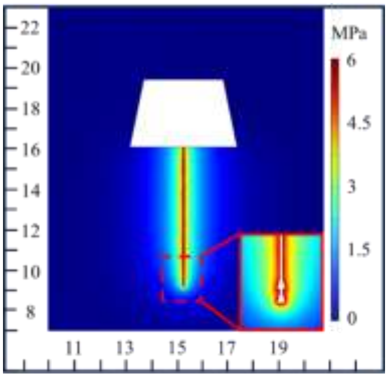
During the grouting process, it is necessary to maintain sufficient pressure to ensure the effective diffusion of the grout, and at the same time avoid excessive pressure causing new cracks. Therefore, determining a reasonable range of grouting pressure is of great significance for the efficient implementation of the grouting process. Based on the experience of on-site engineering, when using the grouting anchor cable grouting process, the common grouting pressure range is 1.0 to 6.0 MPa. Therefore, in order to explore the influence law of different grouting pressures on the diffusion range of the grout, the grout diffusion time was fixed at 10 minutes in the simulation, and six groups of experiments were set up within the pressure range of 1.0-6.0 MPa. The partial cloud diagrams of the grout pressure distribution under different grouting pressure conditions are shown in Figure 2.



(a) grouting pressure 2 MPa



(b) grouting pressure 4 MPa



(c) grouting pressure 6 MPa

Figure 2. The diffusion form of the grout when the grouting pressure is 2, 4 and 6MPa

As can be seen from Figure 2, the diffusion range of the grout increases with the increase of grouting pressure, but the growth rate decreases with the increase of grouting pressure. According to the previous research results, the diffusion range of the slurry in the deep part of the surrounding rock is relatively small, and the difference from the shallow diffusion is obvious[8]. In the expanded hole area, due to the increase in the diameter of the anchoring holes, the initial diffusion area of the grout is enhanced. This is conducive to the grout diffusion of the deep surrounding rock, reduces the unevenness of the grout diffusion between the deep and shallow surrounding rocks, and further increases the thickness of the grout reinforcement ring of the base rock.

By extracting and integrating the original data in the simulation, the diffusion laws of the grout under different grouting pressure conditions were obtained, as shown in Figure 3.

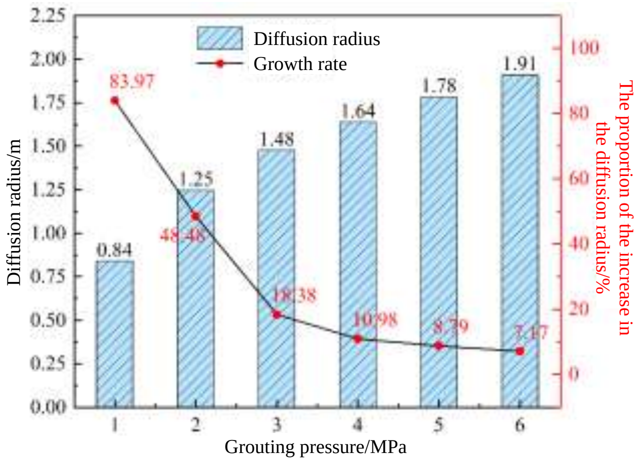


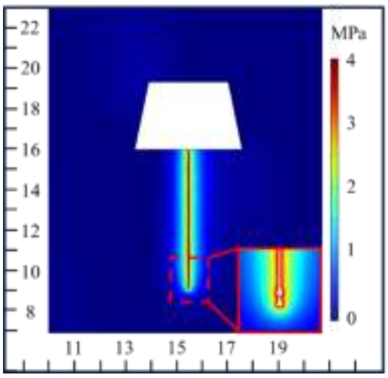
Figure 3. The diffusion morphology of the slurry under different grouting pressures

By comparing the evolution law of the diffusion radius of the liquid in the slurry as shown in Figure 3, its growth process can be initially divided into three stages, namely the rapid diffusion stage, the rapid diffusion stage and the slow diffusion stage. When the grouting pressure rises from 0 MPa to 1 MPa, the diffusion radius of the grout rapidly increases from 0 to 0.84 m, indicating that under low pressure conditions, the grout can quickly fill the surrounding medium and form an initial reinforcing layer. Therefore, this stage is called the rapid diffusion stage. With the further increase of the grouting pressure, when the pressure range is 1-3 MPa, it enters the rapid diffusion stage. At this time, although the diffusion radius of the grout is still expanding, its growth rate slows down significantly. The increase rate of the diffusion radius has decreased from 48.48% to 18.38%, which is much lower than 83.97% in the rapid diffusion stage, indicating that the diffusion process in this stage gradually stabilizes. This might be because as the pressure increases, the diffusion of the slurry is gradually restricted by the surrounding rock structure and pore characteristics. When the grouting pressure increases from 4 MPa to 6 MPa, the diffusion of the grout enters a stage of slow growth. At this time, the growth rate of the diffusion radius further decreases, from 10.98% to 7.17%. This indicates that under high pressure, the flow and filling effect of the slurry have tended to be stable, and the change in its diffusion range is relatively limited.

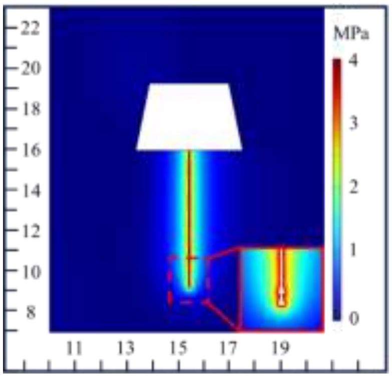
To sum up, increasing the grouting pressure can indeed expand the diffusion radius of the grout. However, as the pressure continuously increases, its contribution to the growth rate of the diffusion radius gradually weakens, and excessive pressure may damage the integrity of the surrounding rock of the base plate. Considering the fragmentation condition of the surrounding rock of the base plate and the energy consumption of the grouting equipment and other practical factors, after a comprehensive analysis, it is recommended to control the grouting pressure within the range of 3 to 4 MPa. Within this pressure range, the slurry can not only fully diffuse in the fractures and pores of the base plate to form an effective reinforcing layer, but also prevent the surrounding rock from being damaged due to excessive pressure, thereby ensuring the overall stability of the base plate. Reasonable grouting pressure not only provides a clear parameter basis for on-site construction, but also helps to achieve a balance between construction effect and equipment energy consumption, providing theoretical support for the practical application of the “expansion-grouting” anchoring technology of base plate anchor cables.

3.2. The influence of grouting time on grout diffusion

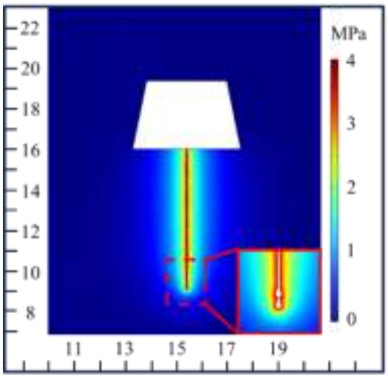
During the grouting construction process, the grouting time has a significant impact on the penetration and diffusion effect of the grout within the surrounding rock. If the grouting time is insufficient, the diffusion of the grout in the surrounding rock is restricted. Especially in the fractured areas far from the grouting holes, due to insufficient power, the fractures are difficult to be fully filled. On the contrary, if the grouting time is too long, although the diffusion range of the grout increases, it will reduce the efficiency of support construction, affect the mining progress, and may lead to the waste of grout. Therefore, reasonably determining the grouting time is the key to ensuring the reinforcement effect and construction efficiency. In actual engineering, since the diffusion state of the grout inside the surrounding rock cannot be directly observed, the grouting time is often judged based on on-site experience. However, choosing the grouting time only based on experience can easily lead to insufficient or excessive grouting, thereby affecting the reinforcement quality. In order to determine the influence of grouting time on the diffusion law of grout more accurately, in this section, 4 MPa is selected as the grouting pressure within the previously determined grouting pressure range, and the grouting time is divided into 12 grades with an interval of 1 minute. The diffusion effect of grout in the surrounding rock under different grouting time conditions is studied through numerical simulation. Since the differences shown in the cloud images at 1-minute intervals are relatively small, it is not conducive to observing the changing trend of the diffusion range. Therefore, in order to more clearly demonstrate the influence of grouting time on grout diffusion, the time interval is adjusted to 4 minutes in Figure 4.



(a) grouting time 4 min



(b) grouting time 8 min



(c) grouting time 12 min

Figure 4. The diffusion forms of the grout at the grouting times of 4, 8 and 12 minutes

By systematically organizing the original data generated by the slurry diffusion at different time points during the simulation process, extracting the curve of the distance between the slurry pressure and the hole wall as well as the specific value of the slurry diffusion radius, the diffusion evolution law of the slurry pressure under the condition of time variables was plotted, as shown in Figure 5.

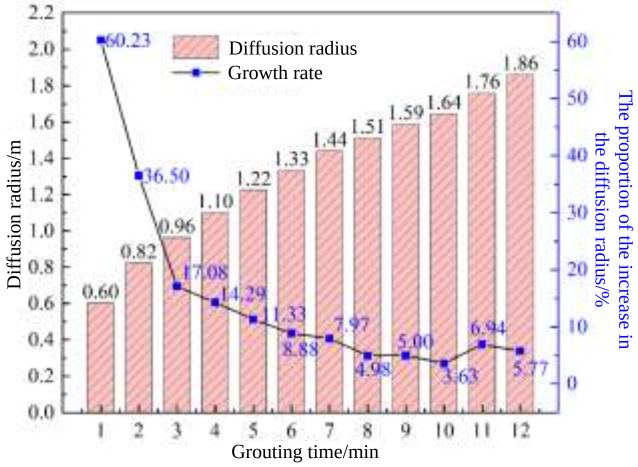


Figure 5. The diffusion law of grout at different grouting times

In Figure 5, the growth rate is represented by the growth ratio of the grout diffusion radius in adjacent grouting time periods. According to the growth rate of the grout diffusion radius, the curve of the grout diffusion range changing with time can be initially divided into three stages: the initial stage, the middle stage and the later stage of grouting. When the grouting time is between 0 and 3 minutes, it is the initial stage of grouting. At this time, the grout pressure in the rock mass is close to zero, the grout penetrates rapidly, and the diffusion radius increases rapidly from 0 m to 0.96 m, with increases of 60.23%, 36.50% and 17.08% respectively, indicating that the initial time of grouting has a significant influence on the diffusion of grout. When the grouting time range was 4 to 7 minutes, the growth rate of the diffusion radius gradually decreased, from 14.29% to 7.97%, and the grout diffusion radius slowly increased from 1.10 m to 1.44 m. When the grouting time reaches 8 minutes, the growth rate of the diffusion radius basically stabilizes and fluctuates around 5%. At this time, the diffusion range of the grout is extremely less affected by the grouting construction time.

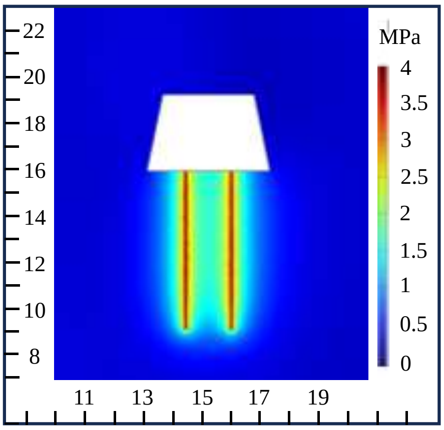
In conclusion, the reasonable grouting time is finally determined to be 8 to 10 minutes to ensure the full diffusion of the grout and the reinforcement of the surrounding rock, while avoiding construction delays.

3.3. The influence of the spacing between grouting anchor cables on grout diffusion

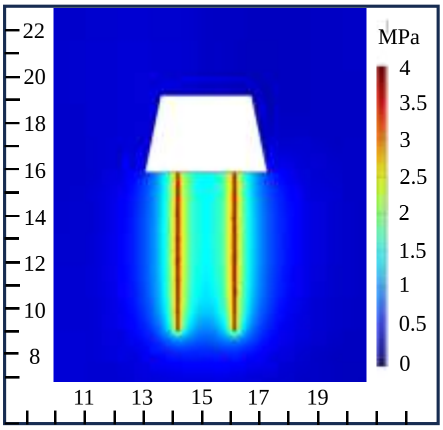
Based on the above research, in this section, with the grouting pressure of 4.0 MPa and the grouting time of 10 min as fixed conditions, the grout diffusion simulation of multi-hole grouting was carried out to explore the influence of the change in the row spacing between grouting anchor cables on the grout diffusion range. During the simulation, one grouting borehole was added on the basis of the original model, and the anchor cable spacings were set at 2.0, 2.5, 3.0, and 3.5 m respectively. The grout diffusion patterns under different anchor cable spacings are shown in Figure 6.

It can be known from Figure 6 that when the spacing of the grouting anchor cable gradually decreases, the grout pressure between the two holes shows a significant overlap phenomenon, forming a concentrated pressure area. When the spacing increases, the slurry pressure no longer superimposes into a complete reinforcing circle. By comparing the diffusion range of the slurry, it can be known that when the anchor cable spacing is 2.0, 2.5, 3.0 and 3.5 m, the corresponding thicknesses of the reinforcement rings are 6.0, 4.0, 2.8 and 0 m respectively. This indicates that as the spacing of the grouting holes increases, the thickness of the reinforcing ring formed between the two holes gradually decreases until an effective reinforcing ring can no longer be formed. As shown in Figure 6 (d), when the anchor cable spacing reaches 3.5m, it is difficult for the slurry to form a tight and uniform reinforcement band. In addition, the diffusion range of the slurry also directly affects the coverage effect of the reinforcement ring. If the spacing of the anchor cables is small, the slurry may not be able to cover the projected area of the entire roadway floor during diffusion. However, the stability of both sides of the roadway is better due to the support of the side corners. On the contrary, when the spacing of the anchor cables increases, although the diffusion range of the slurry in the bottom corner area expands, the superposition effect at the center of the roadway will weaken, which is not conducive to the formation of a stable reinforcement layer directly beneath the floor slab. When designing the grouting anchor cables, the thickness and range of the reinforcement rings need to be comprehensively considered.

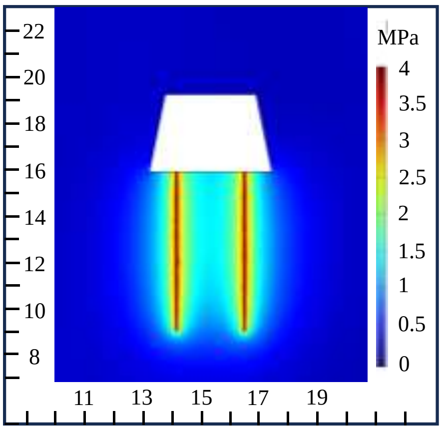
Therefore, it is recommended that the spacing of the anchor cables be controlled between 2.5 and 3.0 meters to effectively balance the diffusion range of the grout and the reinforcement effect of the base plate.



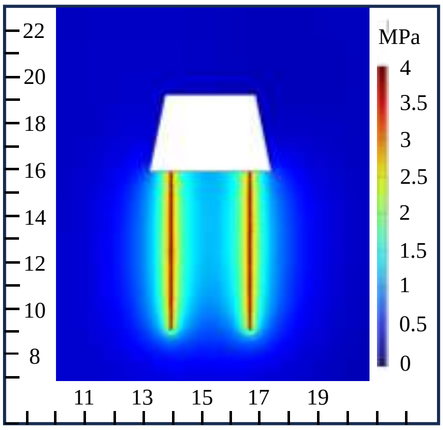
(a) anchor cable spacing 2 m



(b) anchor cable spacing 2.5 m



(c) anchor cable spacing 3 m



(d) anchor cable spacing 3.5 m

Figure 6. Slurry diffusion forms under different anchor cable spacings

4. CONCLUSION

This chapter analyzes the law of slurry diffusion and its influencing factors through the combination of theory and numerical simulation. According to the research results, a reasonable selection of grouting pressure and time can significantly improve the reinforcement effect of the surrounding rock, providing a theoretical basis and technical support for the subsequent engineering practice. The specific conclusions are as follows:

(1) Through the COMSOL Multiphysics numerical simulation software, the influence characteristics of grouting pressure, time and row spacing on the grout diffusion law of the bottom plate anchor cable under the “expansion-grouting” anchoring condition were systematically studied, revealing the law that the grout diffusion radius increases nonlinearly with the increase of grouting pressure; Meanwhile, the phased control effect of grouting time on the diffusion range was expounded. As time increased, the diffusion range expanded and the efficiency gradually decreased and tended to be stable.

(2) The numerical simulation results show that a larger anchor cable spacing is not conducive to the formation of the grout reinforcement circle at the center of the base plate. As the anchor cable spacing increases from 2 m to 3.5 m, the grout diffusion range changes from high overlap to complete separation. When the anchor cable spacing is between 2.5 and 3 m, it can take into account both the bottom Angle and the center of the base plate, forming a closely concentrated grout reinforcement circle for the base plate.

(3) Combined with the actual geological conditions of the 12203 working face in Zhaojiazhai, the grouting parameters for the “expansion-grouting” anchoring of the floor anchor cables were optimized. It was determined that when the grouting pressure was 3-4 MPa, the grouting time was 8-10 minutes, and the anchor cable spacing was 2.5-3 m, the floor anchor cables could ensure the grouting effect and effectively reinforce the floor of the roadway.

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