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Research Article

Study on the Influence of Borehole Water Content on Bolt Anchoring Force in Soft Surrounding Rock

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In order to further reveal the influence mechanism of borehole water content on anchoring force in soft surrounding rock, three different research methods are used. Firstly, through theoretical analysis, it reveals that borehole water content will affect the cohesion of anchoring agent and then leads to the decrease of anchoring force. Secondly, through experimental analysis and numerical simulation of the influence of different boreholes water content on the anchoring force, it indicates that the borehole water content has a weakening effect on the mechanics characteristics of bolts significantly. When the borehole water content is less than 15 mL, the influence of borehole water content on anchoring force is weak for a given borehole length. When the borehole water content is greater than 15 mL, the anchoring force decreases greatly with the increase of borehole water content for a given borehole length and the decline of anchorage force is more than 30%. At the same time, through the experimental analysis, it reveals that the failure type of bolt in weak surrounding rock is the typical failure of anchorage force where the fracture goes far into the surrounding rock. Thus, in practical operation, reasonably controlling the borehole water content (rate) within the critical value can improve the bolt support effect and reduce the support cost.

1. Introduction

As a simple and effective surrounding rock reinforcement technology, bolt support has been widely used in coal mine roadway and achieved good support effect [1, 2].

As the main component of Yunnan-Guizhou coal base, the only large coal base in South China, Guizhou Province, is rich in coal resources. But the coal seam deposit conditions are complex. The coal measure strata are mostly soft strata such as mudstone and siltstone, which brings great difficulties to the roadway support. Due to the widespread existence of joints, fractures, faults, and other structures in the soft surrounding rock, the seepage of underground water is serious. During anchoring, most of the borehole is full of water, which has a great influence on the anchorage ability of the bolt [3, 4].

At present, the influencing factors of bolt anchoring performance mainly include bonding length, type of bolt, surrounding rock temperature, water, etc. [5, 6]. Scholars and abroad have carried out relevant research on the factors affecting the anchoring performance. For example, Wang et al. [7] adopted the test method of national standard and the coal industry standard and, through systematical studies, concluded that the gelation time of the anchorage agent decreased significantly with the increase of temperature. Aghchai et al. [8] proposed an analysis method to determine the shear strength parameters of the bond by using the load displacement curve of the bolt head based on the bolt pull-out test. Wang et al. [9] found that the bolt temperature has a certain impact on its pull-out strength. At 25°C–35°C, the pull-out strength increases with the increase of temperature, and at 50°C–70°C, the pull-out strength decreases. Du et al. [10, 11] studied the anchoring performance of bolt under different bonding length and different drawing rate and obtained that the peak drawing load of bolt will increase with the increase of bonding length and drawing rate, but there is a critical bonding length. Xiao et al. [12] studied the pull-out characteristics of bolts under different anchorage lengths and revealed the pull-out mechanical characteristics and anchorage failure mode of anchor bolts under different anchorage lengths. Wang et al. [13] theoretically deduced the influence of different anchorage lengths on the anchorage performance of bolts. Wei et al. [14] studied that the greater the drawing rate, the greater the peak drawing load of anchor rod, but there is a threshold value of impact energy. Exceeding the threshold dynamic load will reduce the impact resistance of anchor system. Chen et al. [15], through numerical simulation, found that the elastic modulus, strength, and rock strength of binder have a significant impact on the anchoring force of bolt. Gou et al. [16] took the suburban coal mine as the engineering background and showed that the influence on the anchoring force of the resin bolt is greater when the drilling water leaching is greater than 583 mL/min. Zhang et al. [17] concluded that reducing the water content and reducing the temperature in the borehole are two important factors to improve the anchoring force. Zhou et al. [18] used the methods of laboratory test and numerical simulation and concluded that the increase of water content will reduce the pull-out force of bolt and weaken the anchoring performance of anchoring agent. Kim et al. [19] studied the pull-out bearing characteristics of fully grouted bolt (FGR) and ISR in water bearing rock. Hu et al. [20, 21] concluded that the anchoring force of resin bolt decreased with the increase of simulated drilling temperature and water content.

At present, researches on the anchorage characteristics of anchor bolts in weak surrounding rock were rare. Based on the existing research, through theoretical analysis, numerical simulation, and laboratory test, the purpose of this research is to further reveal the influences mechanism of borehole water content on anchoring force in soft surrounding rock, so as to provide references for the on-site bolt support design.

2. Mechanism Analysis of Influence of Borehole Water Content on Bolt Anchoring Force

Assume that the rock and resin anchoring agent are all elastomers; the formula of the adhesion of the adhesive acting on the bolt surface from the end point is [22]

$$\tau_{(x)} = ce^{-(x/D)\sqrt{8K/E}}, \tag{1}$$

where $\tau_{(x)}$ is the adhesive stress of the anchoring agent acting on the bolt surface at point $x_{(\mathrm{MPa})}$, $K = (K_1 K_2 / K_1 + K_2)$, K_1 is the shear stiffness of adhesive, K_2 is the shear stiffness of dangerous rock mass (N/m), E is the elastic modulus (MPa), and D is the diameter of bolt (mm).

Based on the empirical formula of rock elastic modulus and water content [23]:

$$E = E_0 e^{c\omega}, \tag{2}$$

where E_0 is the elastic modulus in dry state (MPa), ω is moisture content (%), and c is an empirical constant less than zero.

Assume that the pull-out force reaches the maximum value $P_{\max}$ when the adhesive fails to the midpoint of the anchorage length; the theoretical calculation formula of $P_{\max}$ of the anchor bolt [24] is as follows:

$$P_{\max} = \int_{l}^{l/2} \alpha\pi \, D\tau_{(x)} \mathrm{d}x. \tag{3}$$

Replace formula (3) with formulas (1) and (2) to obtain formula (4); that is,

$$P_{\max} = \alpha\pi \, d\sqrt[2]{\frac{E_0 e^{cw}}{8k}}[\tau]\left(1 - e^{-(l/2d)\sqrt{8K/E_0 e^{cw}}}\right), \tag{4}$$

where α is the influence coefficient of residual adhesive stress, l is the anchorage length, mm, K is the shear stiffness (N/m), and E is the elastic modulus of the bolt (MPa); d is the diameter of bolt (mm); and τ is the adhesive stress of the anchoring agent acting on the bolt surface (MPa).

It can be seen from formula (4) that the maximum pull-out force of bolt decreases with the increase of water content. Previous studies have shown that [7] the curing strength of anchoring agent is determined by the polymerization rate of unsaturated polyester resin, while the unsaturated resin is polymerized by free radicals. The more inactive the free radical, the lower of the strength of the cured resin. Mostly, the four aspects of the water content in borehole affecting the anchoring force of bolt are as follows: ① The water content in the borehole will dissolve part of the curing agent and reduce free radicals, result in incomplete curing, and reduce the anchoring force of the bolt. ② The water in the borehole will absorb the heat released by the reaction and reduce the activity of free radicals, result in low strength of the cured resin, and reduce the anchoring force. ③ A lot of water will absorb and take away curing agent, polyester, crosslinking agent, etc., result in incomplete curing reaction, and affect the anchoring force of bolt. ④ Cracks for borehole water to outlet are blocked by pressed anchoring agent, result in the dispersion of water droplets into the resin, then reduce the curing strength, and weaken the anchoring force. In summary, the influential mechanism can be shown in Figure 1.

In conclusion, based on the analysis of mechanics and chemical reactions, it is shown that the water content in the borehole will reduce the cured strength of the anchor agent, weaken the adhesion existing between the cured resin and the soft surrounding rock or the bolt, and result in the decline of the anchoring force and the decline of the support effect of bolt.

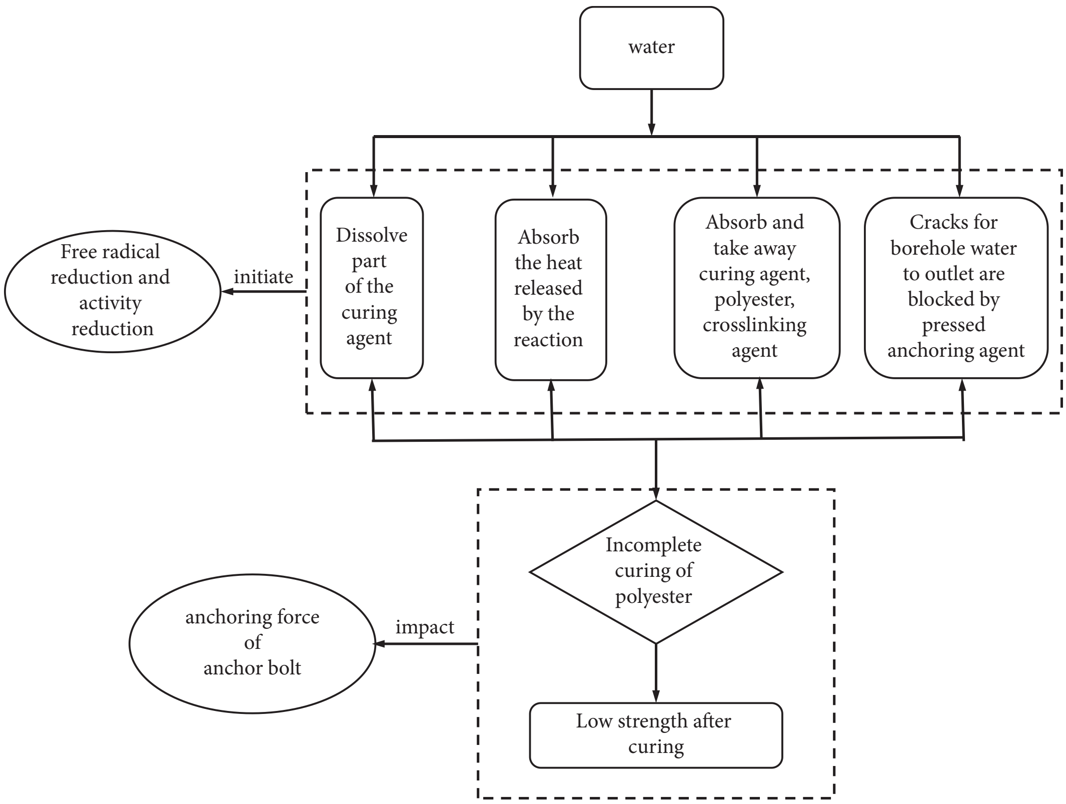

Figure 1: Mechanism of water effect on anchor force.

3. Anchor Pull-Out Test under the Influence of Different Borehole Water Contents in Soft Surrounding Rock

3.1. Test Equipment. QKX-MLB-500 bolt (cable) pull-out creep test system is adopted for the test, which is shown in Figure 2. The maximum pull-out load of the test system is 500 kN, the maximum hold time is 72 h, and the vertical loading trip is 0–150 mm. The programmed loading and unloading value and displacement value can be realized through the control system. At the same time, using the built-in sensors and data acquisition system, all the data can be automatically stored and displayed in real time, and the data can be exported for further processing and analysis.

3.2. Preparation of the Anchorage Test Piece

3.2.1. Determination of the Ratio Number of Similar Materials for Anchoring Surrounding Rock. The anchor surrounding rock in the pull-out test is prepared by mixing river sand, gypsum, lime, water, and other similar simulation materials in a certain proportion. The matching number 555 is determined by strength ratio, and its uniaxial compressive strength is about 1 MPa, which simulates the soft surrounding rock.

3.2.2. Preparation of the Pull-Out Specimen. Size 150 mm × 300 mm (diameter × height) ABS engineering plastic test molds are used for cylindrical anchoring surrounding rock; PVC pipes with outer diameter of 30 mm are used for simulated drilling holes. The detailed preparation steps of the pull-out test piece are as follows: Firstly, similar materials are tamped at the bottom of the test mold with a thickness of 50 mm as the surrounding rock at the bottom of the simulated borehole and to prevent the resin agent from leaking at the bottom of the borehole during the test; secondly the PVC pipe was placed vertically in the test mold center, the pipe wall was brushed with vegetable oil (to facilitate the pulling out of the PVC pipe normal and effectively), and then it was filled with similar materials and tamped. After 24 hours, the PVC pipe was removed for natural maintenance of the anchor specimen. The anchor specimen with simulated drilling holes is finally formed after several days (Figure 3).

In order to make the test conditions similar to the in-site, the test bolts and MSK2335 fast resin agent are provided by coal mine. Various simulation materials and parameters are shown in Table 1.

According to the above preparation methods of anchored surrounding rock and simulated hole, 6 groups of anchor pull-out specimens are prepared which are named A1, B1, C1, D1, E1, and F1. A section of MSK2335 rapid resin agent is adopted for each simulated drilling hole; then 0 mL, 5 mL, 10 mL, 15 mL, 20 mL, and 25 mL water are injected, respectively, to each of the specimens and to simulate the water content of different holes. The bolt was inserted vertically into the anchor test piece; then it was mixed with a hand-held anchor drilling machine for 30 s. Finally, the anchor pull-out test piece is formed for this test after natural maintenance for several days, which is shown in Figure 4.

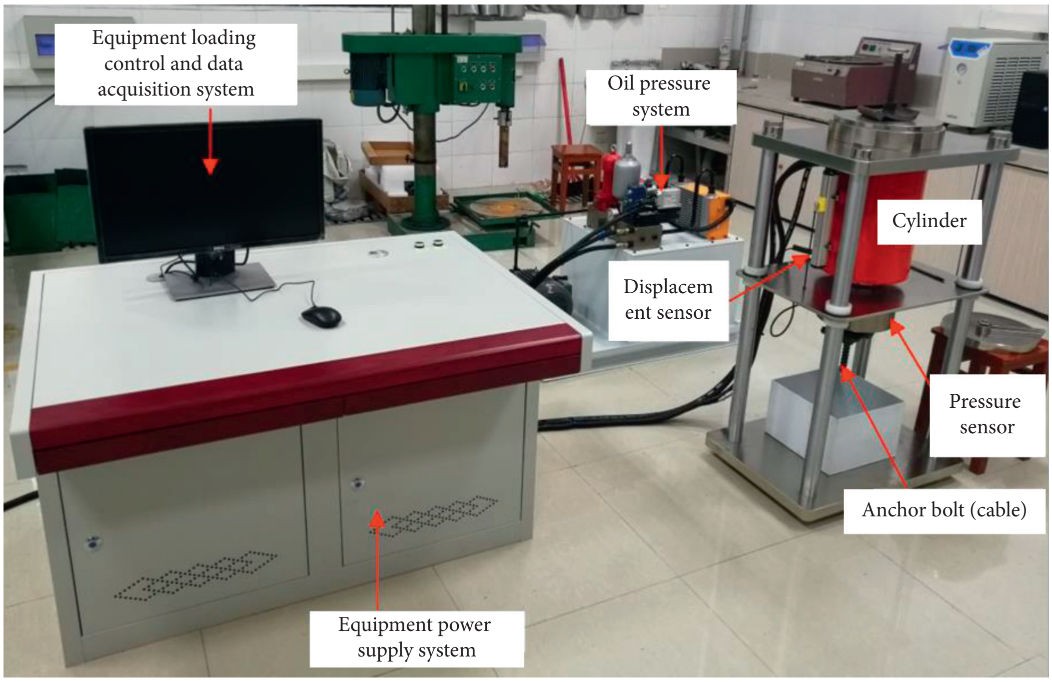

Figure 2: QKX-MLB-500 bolt (cable) pull-out creep test system.

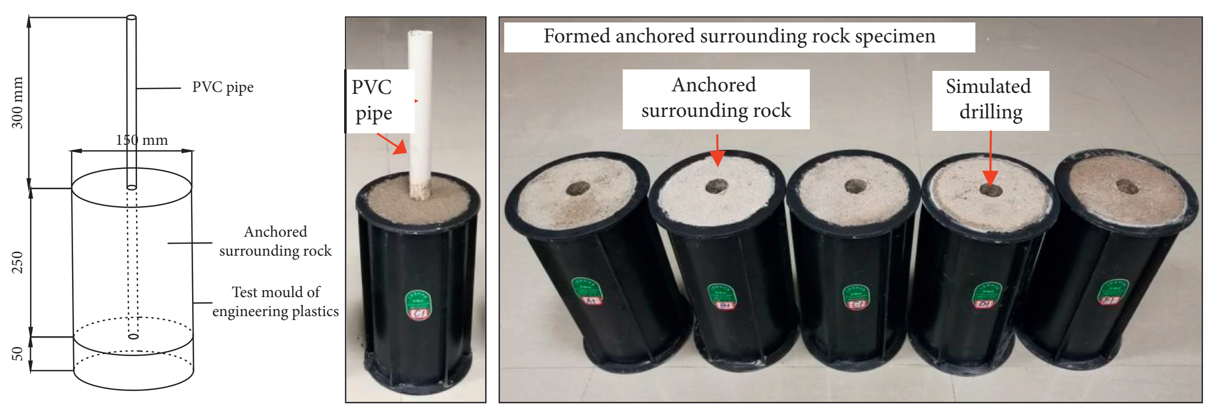

Figure 3: Specimen preparation of anchorage surrounding rock.

Table 1: Simulation materials and parameters.

Name	Length/mm	Diameter/mm	Remarks
Anchored surrounding rock	300	150	Cylinder
Simulated drilling	250	30	—
Bolt	1100	21.6	—
Resin agent	350	23	Quick

3.3. Test Process. The prepared test pieces were moved to the test bench for pull-out test in turn. In order to ensure uniform stress during the pull-out test, the pull-out stroke was preprogrammed, the slow-speed displacement control was adopted, and the pull-out rate was controlled at 5 mm/min till the anchor bolts of each anchor test piece reached the pull-out state. Data collection was stopped after the peak value of the pull-out force was reduced to a certain extent; then the test data was sorted out and analyzed.

3.4. Test Results and Analysis. Figure 5 shows some of these specimens after the pull-out test. It can be seen in Figures 4 and 5 that the bolt in the hole without water injection fits well with the surrounding rock, and the surrounding rock pulled off by anchoring agent after pull-out test was basically not broken. When the hole was injected with 10 mL water, due to part of the anchoring agent dissolved by water and the reduction of free radical activity, cracks appeared between the anchoring agent and the spalled surrounding rock, but

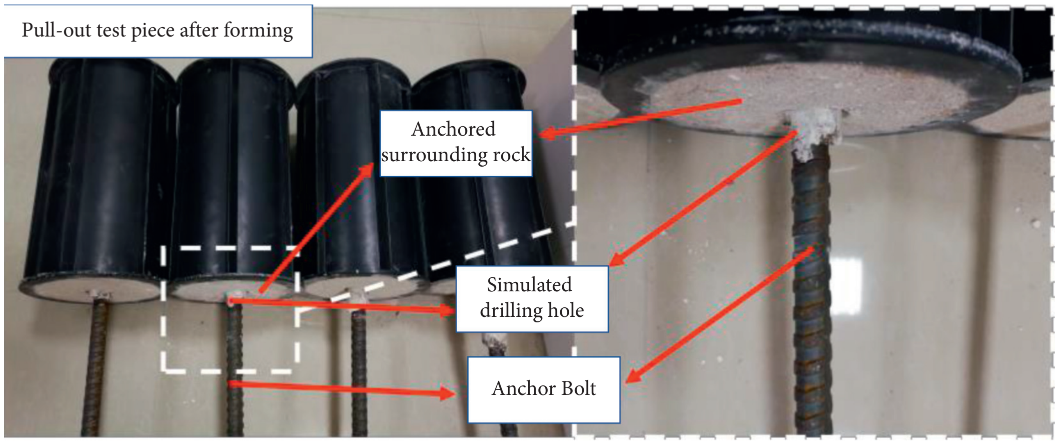

Figure 4: Preparation of the anchorage pull-out specimen (part).

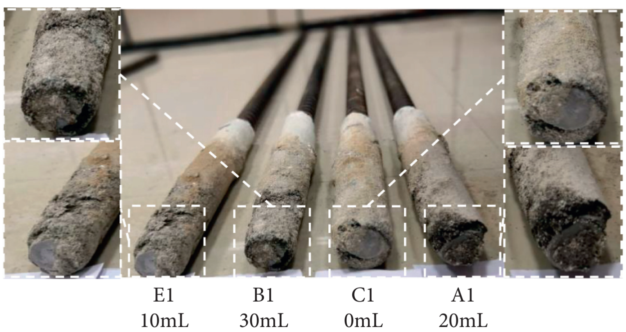

Figure 5: Specimens after the pull-out test (part).

the anchor bolt and the surrounding rock were united without breakage. When the hole was injected with 20 mL water, there were some obvious and large cracks, and the anchorage agent was in good contact with the surrounding rock, but it was broken. When the hole was injected with 25 mL water, the curing reaction was incomplete due to the presence of a large amount of water which absorbed and took away the curing agent, polyester, crosslinking agent, etc. The bonding between the resin agent and the surrounding rock was very poor and falling off occurred. Compared with other test pieces, the integrity of the anchor agent and the spalled surrounding rock was very poor. Based on this, it can be concluded that the failure type of the bolt in the pull-out test is a common failure of bolt, which is the typical bolt bond failure of fractures going deep into the surrounding rock [19]. The water content in the borehole affects the pull-out force of the bolt and the performance of the anchoring agent. The more the water content in the borehole, the worse the integrity of the anchoring agent and the surrounding rock after pull-out.

The data processing software of the test system was used. After the end of the test the data was extracted; the displacement and loading curves of pull-out specimens with different water content were obtained through post-processing. Taking the No. E1 anchor pull-out specimen as an example, Figure 6 shows the typical pull-out force displacement curve, which is divided into three stages of ABC.

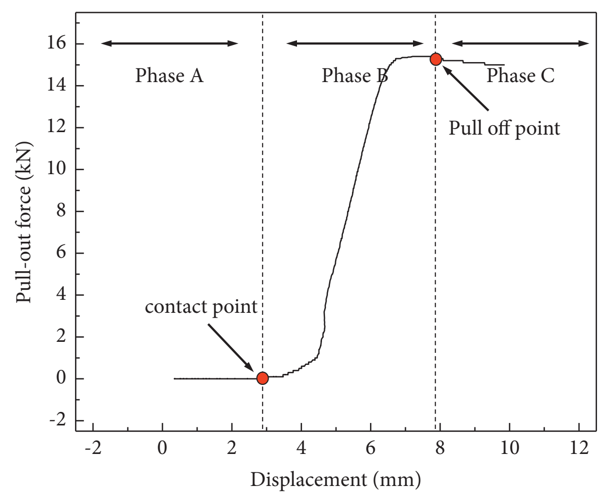

Figure 6: Loading and displacement curve.

Stage A is from the beginning of oil cylinder action to the pressure sensor contacted with the anchor, so the loading in this process is 0 kN. Stage B refers to the idea that after the pressure sensor contacted with the anchor, with the increase of loading displacement, the pull-out force rises rapidly till the anchor bolt is pulled off. Stage B is followed by C: the pull-out force begins to decrease continuously under the action of residual anchoring force. At the end of stage B, the peak pull-out force 15.4 kN is the anchor force of the bolt which is on the pull-out point.

Figure 7 shows the pull-out test results of anchorage specimens with different water contents.

It can be seen that the anchoring force of the anchor specimen without water injection in the borehole is 17.0 kN. With different water content, the maximum pulling force of the anchor specimen is from 11.9 kN to 15.4 kN, with an average of 13.7 kN. Compared with the anchor specimen without water injection in the borehole, the anchoring force decreases significantly. Thus, the water content in the borehole will weaken the bonding force between the anchor agent, the surrounding rock, and the bolt and then reduce the anchoring effect. When the simulated borehole water

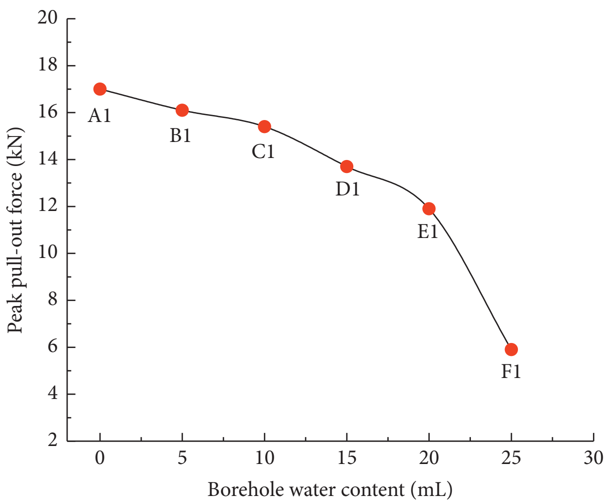

Figure 7: Point line diagram of maximum loading of specimens with different water contents.

content increases from 0 mL to 15 mL, the peak pulling force of anchor bolt decreases gently, with a decrease of 3.3 kN, which is about 19.4% lower than that without ponding. When the water content in the simulated borehole is 15 mL to 25 mL, the peak pulling force of the anchor declined significantly. When the water content of the drill hole is 20 mL, the drawing force drops sharply, with a decrease of 11.1 kN, which is only 35% of the no water content. It can be concluded that the adhesive force is very weak when the water content of the drill hole exceeds the critical value, and the anchoring effect is very poor because excessive water influenced the gel process of the resin.

The above tests show that the borehole water content (rate) has a significant influence on the anchoring force when the borehole length was given. In this test, the simulated borehole length is 350 mm, and the borehole water content has a critical value of 15 mL. Because the length of the borehole does not change, the borehole water content rate can be calculated when the borehole water content is certain. When the borehole water content (rate) exceeds 15 mL, the anchoring force decreases significantly. In practical engineering, due to the complexity of underground mining conditions, it is very difficult to completely avoid borehole water. Therefore, when the borehole length is given, it is important to reasonably control the borehole water content within the critical value, so as to improve bolt support effect and to reduce the support cost.

4. Numerical Simulation Analysis of Influence of Borehole Water Content on Bolt Anchoring Force

4.1. Model Determination and Meshing. $FLAC^{3D}$ was selected for simulation research. A single bolt fixed in a small range of surrounding rock in three-dimensional space is used for the numerical simulation object. Size × wide × Height = 150 mm × 150 mm × 300 mm which is consistent with the test specimen; the diameter of bolt was 22 mm and the length is 1000 mm, between bolt and surrounding rock is annular anchoring unit (grout), the thickness of grout is 4 mm, and anchoring length is 250 mm. The horizontal displacement is fixed around, the horizontal and vertical displacement are fixed at the bottom, and the top is a free boundary. A fixed pull-out rate of 1e-7 is applied only at the top of the bolt. The bolt is hypostatic. The linear elastic model is used for bolt, and the Mohr Coulomb model is used for the surrounding rock and grout. A load of 4 MPa is set for the rock to simulate the actual confining pressure on the whole anchorage body. A contact surface is set between the bolt and grout, grout and surrounding rock, and its parameters (normal stiffness, shear stiffness, etc.) are calculated according to the actual grout and surrounding rock parameters. The cohesion of the contact surface between surrounding rock and anchorage agent is 1e7, the internal friction angle is 35°, the normal stiffness is 4.3e11, and the shear surface stiffness is 4.3e11; the cohesion of the contact surface between anchoring agent and anchor rod is 1e5, the internal friction angle is 25°, the normal stiffness is 2.25e11, and the shear surface stiffness is 2.25e11. The grid division is shown in Figure 8; it is divided into 12800 zones and 13371 grid points. The material parameters of surrounding rock, bolt, and grout are shown in Table 2.

In order to simulate the weakening effect of the mechanical properties of the bolt when the mechanical parameters of the anchoring agent are reduced which is caused by the existence of water in the borehole, the variation characteristics of bolt pulling force were simulated, respectively, when only the friction angle and cohesion of grout were changed, under the same external conditions.

4.2. Numerical Simulation Results and Analysis

4.2.1. Loading and Displacement Curve of the Bolt. The loading and displacement curve of the bolt when the cohesion is 8 Mpa and the internal friction angle is 38° is shown in Figure 9. It can be seen that the surrounding rock moves near the orifice at the end of the bolt at point A. Then after point A, it enters the AB stage. With the increase of displacement, the bolt pull-out force increases rapidly. At this stage, the displacement of surrounding rock increases significantly and gradually expands from the orifice position at the anchor end to the surrounding area. With the increase of displacement, the bolt pulls off and the surrounding rock is in a critical state at the point C. Then it is CD section; the surrounding rock is damaged at this stage. Due to the effect of residual anchorage strength, the bolt pull-out force gradually decreases with the increase of displacement until it arrives point *D*, the anchorage body loses its anchoring capacity, and the bolt pull-out force no longer changes with the increase of displacement. This is consistent with the test shown in Figure 6.

4.2.2. Pull-Out Load and Displacement Curves of Bolts with Different Water Contents. Figure 10 shows the pull-out load and displacement curve of bolt with different water content in boreholes. It can be seen that the water content of anchor

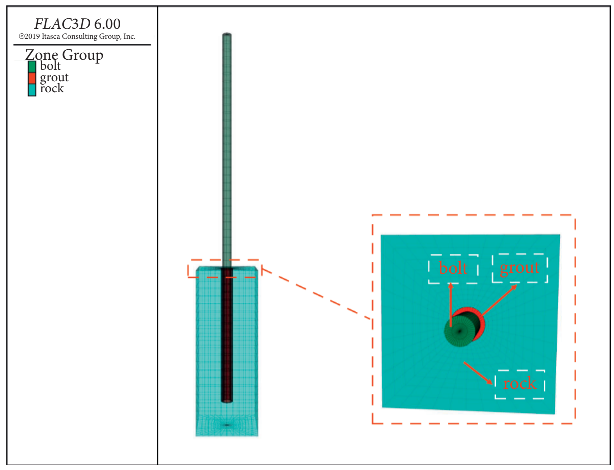

Figure 8: Numerical calculation model.

Table 2: Mechanical parameters of simulated materials.

	Bulk modulus K/GPa	Shear modulus G/GPa	Cohesion C/MPa	Internal friction angle φ/ (°)	Density (g·cm^{-2})
Bolt	143	82	—	—	7.5
Grout	7.5	3	8	38	2
Rock	2.8	1.6	2.2	22	2.5

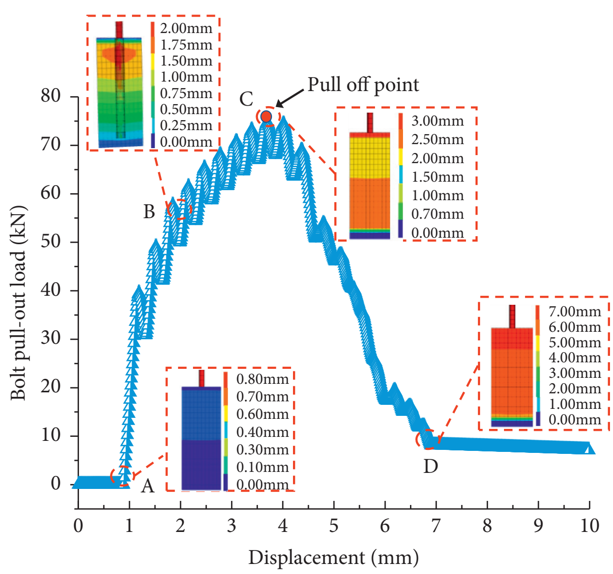

Figure 9: Loading and displacement curve of the bolt.

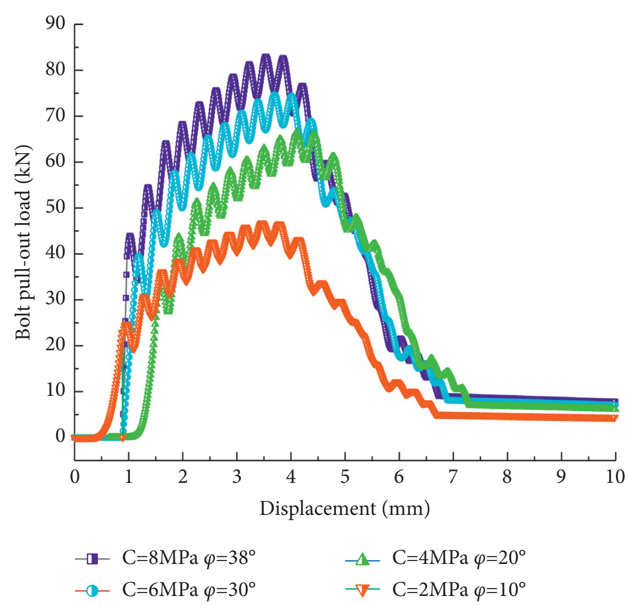

Figure 10: Pull-out load and displacement curves of bolts under different cohesion and interior friction angles.

hole has a significant influence on the shape of pull-out load and displacement curve.

When the cohesion is 8 MPa and the internal friction angle is 38°, the peak pull-out force is 82.98 kN. With the decrease of cohesion and internal friction angle, when $C = 6$ MPa and $\varphi = 30°$, the peak pull-out force is 74.68 kN, which is 10% lower than that without water. When $C = 4$ MPa and $\varphi = 20°$, the peak pull-out force is 66.11 kN, which is 20.3% lower than that without water. When $C = 2$ MPa and $\varphi = 10°$, the peak pull-out load is 46.56 kN, which is 43.9% lower than that when there is no water. It conclude that the peak pull-out load decreases gradually with the decrease of the value of C and φ. Because the water content in the borehole will reduce the value of C and φ, it is consistent with the results of laboratory pull-out test. That is, the parameters such as internal friction angle and cohesion of the anchor agent will decrease by the influence of water and other factors during curing. The cohesive properties are weakened greatly, which eventually leads to the decrease of bolt pull-out load. Therefore, the results show that the mechanics characteristics of bolt support can be weakened by the water content in borehole significantly.

5. Conclusion

The main conclusions of this research are as follows:

(1) The mechanics characteristics of bolt support can be weakened by the water content in borehole significantly. The water content in the borehole will affect the curing speed of the anchor agent, reduce the bonding ability of the anchor agent by reducing the C and φ value and weaken the strength of the anchor agent after being cured, and have a significant influence on the conditions of bolt support.

(2) The failure type of water bearing anchor bolt in soft surrounding rock is a typical bond failure in which the fractures go deep into the surrounding rock. The more the water content in the borehole, the worse the integrity of the surrounding rock after pull-out of the bolt.

(3) When the water content in the borehole increases, the anchoring force of the bolt decreases. When the borehole length is given (for example 350 mm), there is a critical value of borehole water content (rate): when the borehole water content is less than 15 mL, the bolt anchoring force decreases gently. When the borehole water content is more than 15 mL, the bolt anchoring force decreases significantly, with a decrease of more than 30%. Therefore, in practical engineering, when the borehole length is given, it is important to reasonably control the borehole water content (rate) within the critical value, in order to improve bolt support effect and reduce the support cost and to improve mining safety.

Data Availability

The data used to support the conclusions of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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