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Influence Mechanism and Parameter Optimization of 40° Wedge-shaped Reaming Length on Mechanical Bearing Characteristics of Anchorage System

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Abstract: In deep roadways with soft surrounding rock, the anchorage section of conventional cylindrical rock bolts relies on the bonding and friction at the interface between the anchoring agent and the surrounding rock for load transfer, which is prone to issues such as localized stress concentration in the anchoring agent, rapid development of plastic damage in the surrounding rock, and interface debonding failure. These problems make it difficult for the ultimate anchoring force of the bolt to meet the support requirements under high in-situ stress conditions. This study systematically quantifies the coupling relationship among the 40° wedge-shaped reaming length, anchoring force, and surrounding rock damage. A three-dimensional bolt–anchoring agent–surrounding rock numerical model was established using ABAQUS. With the wedge-shaped reaming angle fixed at 40°, five groups of reaming length conditions—4 cm, 6 cm, 8 cm, 10 cm, and 12 cm—were set up for uniaxial pull-out simulations to reveal the strengthening mechanism of 40° wedge-shaped reaming anchorage. The simulation results reveal that reaming length plays a significant role in modulating the mechanical state of the anchoring system. For short reaming lengths (4–6 cm), the reinforcement effect remained limited and the anchoring agent stress was highly localized near the wedge tip. In the medium range (8–10 cm), the stress within the anchoring agent became more evenly distributed over the anchorage length, while plastic damage in the surrounding rock remained dispersed and non-interconnected; under these conditions, the bolt anchoring force showed the largest improvement, exceeding that of conventional straight-hole bolting by more than 42%. Once the reaming length surpassed 10 cm, the plastic zone in the surrounding rock became interconnected and softened, and the incremental gain in anchoring force diminished markedly. Based on the mechanical response and overall load-bearing performance of the system, 10 cm is identified as the optimal reaming length for the 40° wedge-shaped configuration. These results provide a quantitative reference for designing high-pressure water-jet reaming parameters in deep soft-rock roadways.

Keywords: Soft Surrounding Rock; 40° Wedge-shaped Reaming; Reaming Length; Bolt Anchoring Force; Anchoring Agent Stress; Surrounding Rock Plastic Damage; Numerical Simulation.

1. Introduction

With increasing mining depth in China, deep roadways are increasingly affected by high geostress and fractured wall rock, where traditional support systems often fail to ensure long-term stability [1, 2]. In "three-soft" roadways—characterized by weak roof, coal, and floor strata—the surrounding rock exhibits low bearing capacity and sustains deformation over prolonged periods. Conventional bolt anchorage relies on the bonding and frictional resistance at the anchoring agent interface for load transfer, which tends to induce significant stress concentration at the anchorage end. This frequently leads to interfacial shear slip, debonding, and other failure phenomena, resulting in a low utilization efficiency of the ultimate bolt anchoring force and rendering it difficult to effectively control large deformations and support instability in the surrounding rock. Consequently, anchorage failure and support optimization in deep roadways have become key research directions in the industry [3].

To overcome the inherent limitations of conventional straight-hole anchorage, reaming anchorage technology has been progressively applied in the field of soft surrounding rock support. This technology reconstructs the load transfer mechanism, transforming the single bonding-friction load-bearing mode into a composite load-bearing system combining bonding-friction and mechanical interlocking [4, 5]. It not only enlarges the anchorage contact area but also generates circumferential confining pressure through radial compressive force, thereby comprehensively enhancing the overall performance of the anchoring system [6, 7]. Numerous scholars have conducted diversified research on reaming anchorage. Through field tests and mechanism analysis, the improvement effect of bottom-hole reaming on anchorage performance has been verified, the 40° positive wedge shape has been identified as the optimal reaming structure for soft surrounding rock, and corresponding positive wedge-shaped reaming tools have been developed [8, 10]. By means of numerical simulation and laboratory pull-out tests, the progressive failure characteristics throughout the entire bolt pull-out process and the instability laws of the anchoring structure have been analyzed, and the mechanical behaviors of reaming anchorage in soft coal-rock masses have been systematically summarized [11, 14]. In addition, some studies have investigated the damage evolution laws of anchored surrounding rock and the synergistic effects with overall support in soft-rock roadways under actual mining conditions [15, 17].

However, existing studies have notable limitations: the research focus has predominantly been directed toward aspects such as the number of reaming sections, support materials, and interface characteristics [18, 20], while systematic quantitative analyses of the coupling relationships among reaming length, anchoring agent stress, surrounding rock plastic damage, and ultimate anchoring force remain lacking. Given that 40° has been established as the optimal reaming angle, the regulation mechanism of different reaming

lengths on the anchoring system remains unclear. To address this issue, the present study develops a 3D finite element model in ABAQUS that incorporates the bolt, resin anchor, and surrounding rock as an integrated system. With the wedge angle fixed at 40°, a series of pull-out simulations are performed across a range of reaming lengths to evaluate their effect on anchorage capacity. Stress distributions, plastic damage patterns, and ultimate pull-out forces are extracted and analyzed to identify the governing mechanisms by which reaming length modulates system performance. The results are intended to inform parameter selection and field implementation of wedge-shaped reaming anchorage in deep soft-rock conditions.

2. Numerical Model and Test Scheme

2.1. Construction of the Three-Dimensional Numerical Model

Table 1. Mechanical parameters of model materials

Material	Elastic modulus/GPa	Poisson's ratio	Density/(kg · m^{-3})
Soft surrounding rock	2.8	0.32	2200
Resin anchoring agent	8.5	0.25	1800
Rebar bolt	200	0.20	7850

A three-dimensional integrated numerical model comprising the bolt, resin anchoring agent, and soft surrounding rock was established using the ABAQUS finite element software, aiming to minimize boundary size effects and faithfully reflect the actual mechanical response of the reaming anchorage system during the pull-out process. The overall dimensions of the surrounding rock are 300 mm × 300 mm. The rebar bolt has a diameter of 20 mm and a total length of 300 mm. The base borehole diameter is 24 mm, and the anchorage hole depth is 250 mm.

The surrounding rock follows the Mohr–Coulomb elastoplastic criterion, whereas both the resin anchor and the bolt are treated as linear elastic materials. Contact interactions at the bolt–anchor and anchor–rock interfaces are defined using a bonding–friction formulation to capture slip, debonding, and localized failure during pull-out. Mesh refinement is concentrated in the anchorage zone and wedge-shaped region to improve solution accuracy, with a progressively coarser mesh away from these areas. A mesh independence study was performed, and the resulting error was maintained between 5%-10%.

2.2. Simulation Condition Setup

With the wedge-shaped reaming bevel angle fixed at 40°, only the axial length of the reaming section is varied. Five comparative working conditions are established, designated as K-4, K-6, K-8, K-10, and K-12, corresponding to reaming lengths of 4 cm, 6 cm, 8 cm, 10 cm, and 12 cm, respectively.

Uniform boundary and loading conditions are applied: the bottom surface of the surrounding rock is fully fixed, and normal displacement constraints are imposed on the four lateral sides. Displacement-controlled uniaxial pull-out loading is applied at the free end of the bolt until interfacial debonding failure occurs in the anchoring system. At the peak ultimate pull-out force moment for each condition, two sets of nephogram data are extracted: 1) the overall Mises stress nephogram of the anchoring system (bolt + anchoring agent + wedge-shaped surrounding rock); and 2) the cross-sectional stress and plastic damage nephograms of the surrounding rock within the anchorage section. Simultaneously, the ultimate anchoring force values for each condition are statistically recorded.

3. Analysis of Ultimate Stress Nephograms of the Anchoring System under Different Reaming Lengths

Based on the two sets of nephograms at the ultimate pull-out load moment, this section analyzes the regulation law of reaming length on the stress state of the anchoring system from two dimensions: (1) the overall Mises stress distribution in the anchoring agent, and (2) the stress and plastic damage evolution in the surrounding rock within the anchorage section.

3.1. Overall, Mises Stress Distribution of The Anchoring System under Different Reaming Lengths

As shown in Figure 1, the variation in reaming length significantly affects the distribution pattern, stress concentration location, and peak magnitude of the overall Mises stress in the anchoring system under ultimate pull-out load. The overall behavior can be categorized into three stages: short reaming length, medium reaming length, and excessive reaming length.

In the short reaming length stage (K-4, K-6), due to the limited axial length of the wedge-shaped bevel, the mechanical interlocking load-bearing effect has not been fully established. The high-stress zones in the anchoring agent are mainly concentrated within a narrow range from the borehole entrance to the vicinity of the wedge tip, with stress decaying rapidly along the axial direction, and the anchoring agent in the deeper section participates less in load bearing. Among these, the K-4 condition exhibits a peak Mises stress in the anchoring agent of 160.6 MPa, which is the highest among all working conditions, indicating that the anchoring agent is more prone to localized shear yielding or plastic failure under short reaming length conditions. Meanwhile, the wedge-shaped surrounding rock region remains predominantly at a low stress level, suggesting that the surrounding rock has not yet fully participated in load bearing, and the system relies primarily on the single friction effect of the anchoring agent interface for load transfer, resulting in concentrated stress and relatively low load-bearing efficiency.

In the medium reaming length stage (K-8, K-10), as the reaming length increases, the effective contact area of the wedge-shaped bevel continuously expands. As the reaming length increases to the medium range, the effective contact area along the wedge expands substantially. Stress within the anchoring agent becomes more evenly distributed along the anchorage length, and the peak value declines markedly. In the K-10 case, for instance, the peak stress drops to 120 MPa—a reduction of about 25.3% relative to K-4—

suggesting that the anchor remains predominantly elastic with only minor localized yielding. More significantly, the high-stress region in the adjacent wedge-shaped rock forms a continuous band along the bevel, allowing the applied load to be transmitted more effectively into a broader rock volume. This marks a transition from localized stress concentration toward a more distributed, cooperative load-bearing mode, accompanied by a clear improvement in overall system efficiency.

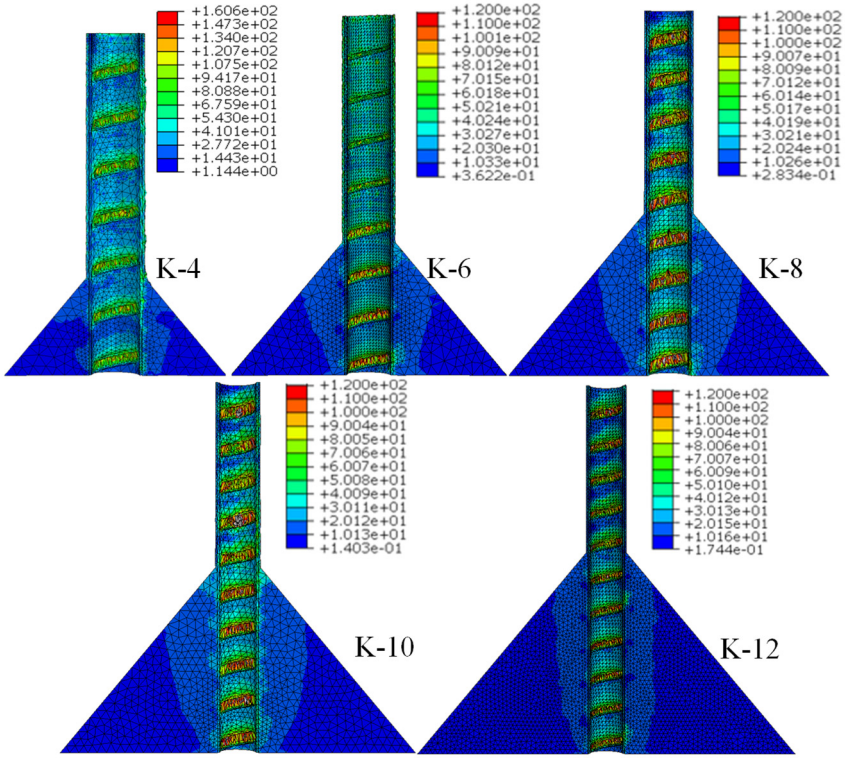

Figure 1. Overall Mises stress nephograms of the 40° wedge-shaped reaming anchoring system with different reaming lengths under ultimate pull-out load

For the excessive reaming length case (K-12), although the contact area continues to grow, the surrounding rock has approached or surpassed its elastic limit, and its confining capacity begins to degrade. Some stress concentration reappears at the distal end of the anchor, and the uniformity of stress distribution is slightly inferior to that observed in K-10. Concurrently, the low-stress zone at the bottom of the wedge-shaped bevel expands, indicating that the rock's effective confinement diminishes after undergoing plastic softening. These observations indicate that extending the reaming length does not produce a linear improvement in anchorage performance; once the rock enters a pronounced softening stage, the benefit of increased contact area is partially negated by strength degradation of the surrounding medium.

3.2. Stress and Plastic Damage Evolution Laws of Surrounding Rock in The Anchorage Section under Different Reaming Lengths

Figure 2 reveals that the stress and plastic damage fields within the surrounding rock vary considerably with reaming length, implying that the reaming extent not only governs the stress state of the anchoring agent but also fundamentally reshapes the load-transfer mechanism and failure behavior of the surrounding rock mass.

For short reaming lengths (K-4, K-6), the surrounding rock exhibits relatively low overall stress, with high stress confined to a small zone near the wedge tip. Plastic damage appears as scattered narrow bands that do not connect. Under such conditions, due to the limited length of the wedge-shaped bevel, the radial compressive force induced by bolt pull-out cannot be fully transmitted to the deep surrounding rock. The circumferential confining pressure provided by the surrounding rock is relatively weak, resulting in limited constraint on the anchoring agent, and the anchoring system is more prone to interfacial debonding and localized failure.

Under medium reaming length conditions K-8 and K-10, the high-stress zone of the surrounding rock is able to completely cover the entire wedge-shaped reaming bevel, forming a relatively continuous compressive pressure ring along the anchorage axial direction. The plastic damage is uniformly distributed and dispersed along the bevel; although localized damage occurs, no extensive through-going softened zone is formed overall, indicating that the surrounding rock still retains a relatively intact rigid load-bearing matrix. Among these, the K-10 condition exhibits the most balanced damage distribution in the surrounding rock, without any significant localized softening zone, and is capable of providing stable and uniform circumferential confining pressure to the anchoring agent under ultimate load. Consequently, the anchoring agent exhibits the most reasonable stress state, and the anchoring system achieves the optimal cooperative load-bearing capacity.

Under the excessive reaming length condition K-12, the radial compressive force generated by the wedge-shaped bevel has exceeded the yield bearing capacity of the soft surrounding rock. The plastic damage zone in the surrounding rock expands significantly and begins to become interconnected, forming a continuous plastic softening zone. Meanwhile, although the high-stress zone still exists, its peak level decreases slightly, indicating that the surrounding rock

can no longer effectively sustain its original confinement function after softening. Although the anchorage interlocking area is further increased at this stage, the integrity of the surrounding rock matrix is compromised, and the confinement effect is lost, leading to a disordered stress state in the anchoring agent and ultimately a marked deceleration in the growth rate of the anchoring force.

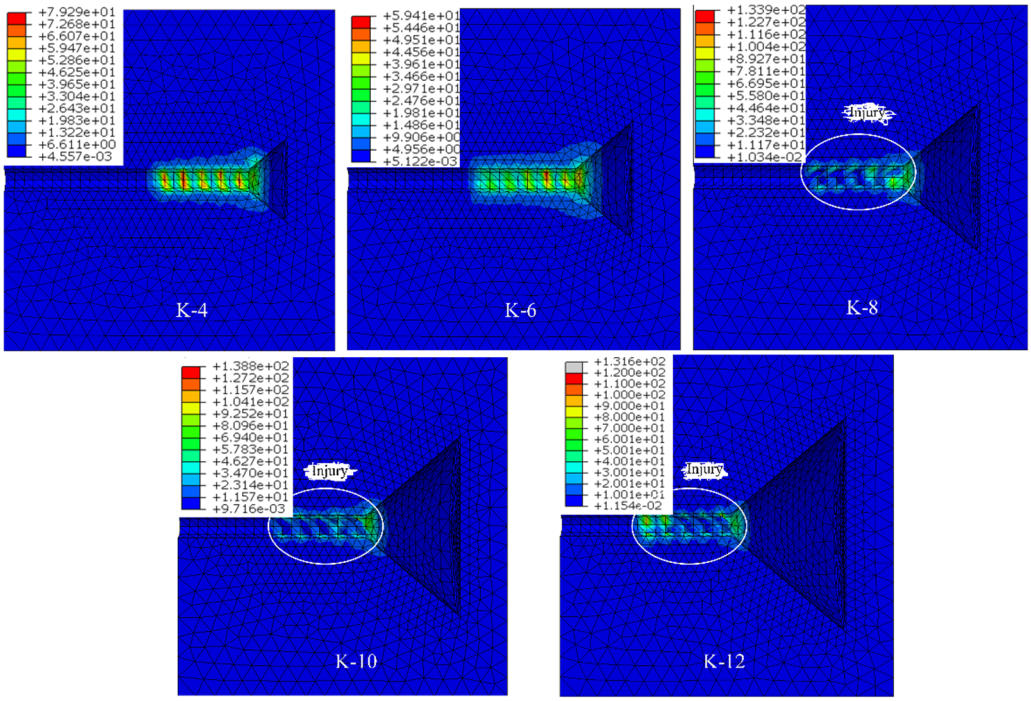

Figure 2. Mises stress and plastic damage nephograms of surrounding rock profiles in the anchorage section for 40° wedge-shaped reaming with different lengths under ultimate pull-out load

3.3. Quantitative Influence of Reaming Length on The Ultimate Bolt Anchoring Force

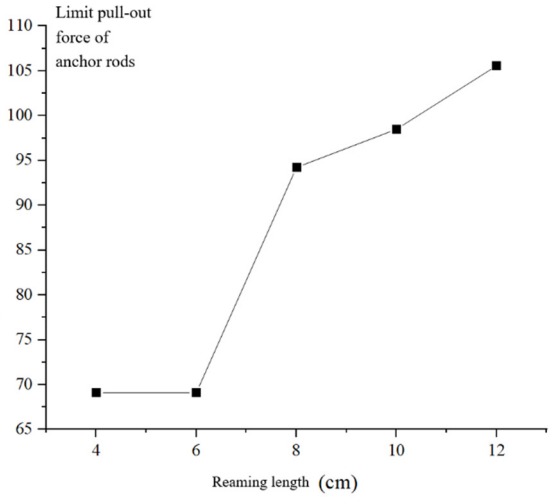

Figure 3. Relationship curve between reaming length and ultimate bolt pull-out force

As shown in Figure 3, the reaming length exerts a significant influence on the ultimate bolt anchoring force, exhibiting typical staged characteristics.

At reaming lengths of 4 cm and 6 cm, the ultimate pull-out force stayed at roughly 69 kN with negligible variation. This plateau suggests that for short reaming lengths, mechanical interlocking and rock confinement have yet to become effective, leaving the anchorage reinforcement rather limited.

At K-8, the pull-out force jumped to 94 kN—an increase of about 36.2% over K-6—indicating that wedge-shaped reaming begins to effectively engage the surrounding rock in load transfer, with the composite mechanism taking a dominant role. At K-10, the force reached 98.5 kN; the increment over K-8 was smaller, suggesting that the reaming length is approaching the upper bound of the optimal range. The K-12 case produced the highest pull-out force among all conditions at 105.8 kN, yet the gain over K-10 was merely 7.4%, with the growth slope narrowing considerably. This indicates that while further extending the reaming section still increases capacity, the marginal returns have diminished substantially, accompanied by an elevated risk of widespread rock damage.

Overall, the relationship between reaming length and ultimate anchoring force is not a simple linear one, but rather exhibits a three-stage evolutionary characteristic: "stable low load — rapid growth — slow growth." Among these, the reaming length interval of 6–10 cm represents the most significant range for anchoring force enhancement, while the length around 10 cm demonstrates a favorable balance between performance improvement and efficiency.

4. Intrinsic Mechanism of 40° Wedge-Shaped Reaming Length in Regulating Anchoring Force

4.1. Load-Bearing Mode and Stress Regulation Mechanism of The Anchoring Agent

Wedge-shaped reaming anchorage relies on the synergistic cooperation between the bonding-friction of the anchoring agent and the wedge-shaped mechanical interlocking. The reaming length directly determines the formation effectiveness of the composite load-bearing system and the stress distribution state of the anchoring agent. Under short reaming length conditions, the effective contact area of the

wedge-shaped bevel is limited, and the anchoring system primarily relies on the interfacial friction between the anchoring agent and the surrounding rock for load transfer, with the mechanical interlocking effect accounting for an extremely low proportion. The anchoring load is concentrated at the front end of the anchorage, resulting in a very limited increase in anchoring force. As the reaming length gradually increases, the effective range of the wedge-shaped bevel continuously expands. The axial tensile force of the bolt is decomposed into interfacial shear force and radial compressive force on the surrounding rock, and the composite load-bearing system, in which bonding-friction and mechanical interlocking work synergistically, gradually takes shape. The anchoring load can then be diffused to a wider range of surrounding rock, and the anchoring force is significantly enhanced. When the reaming length becomes excessive, the radial compressive force exceeds the yield strength of the surrounding rock, leading to plastic softening of the surrounding rock and substantial weakening of the mechanical interlocking effect, and the growth of anchoring force enters a bottleneck. This finding implies that the reaming length should be matched to the load-bearing capacity of the surrounding rock—simply increasing the reaming extent does not guarantee proportional gains in performance.

Below a critical reaming length of about 7 cm, the radial compression from the wedge bevel fails to generate a continuous circumferential confining pressure zone, and mechanical interlocking remains inadequately developed. Once this threshold is exceeded, a continuous confining zone forms along the anchorage and the composite mechanism becomes active, producing a sharp rise in anchoring force. This threshold behavior accounts for the abrupt 36.2% increase observed between the 6-cm and 8-cm cases.

Reaming length also modifies the effective contact area of the anchoring system, thereby influencing the degree of stress concentration within the anchor. Increasing the reaming length expands the contact between the anchoring agent and the rock, reducing the unit-area stress under a given load and mitigating localized stress concentrations. At short reaming lengths, the limited contact area produces pronounced stress concentration near the wedge tip, rendering the anchor susceptible to shear yielding and cracking. At a reaming length of about 10 cm, the stress field within the anchor becomes nearly uniform, the peak stress drops substantially, and the anchor operates predominantly in an elastic regime—allowing full mobilization of interfacial bond strength. Beyond 10 cm, however, rock softening reduces confinement effectiveness. Although the contact area continues to expand, stress uniformity deteriorates, and further optimization of the anchor stress state is constrained by both the rock's bearing capacity and interface stability.

4.2. Surrounding Rock Confinement and System Failure Evolution Mechanism

During bolt tensioning, the wedge bevel imposes radial compression on the surrounding rock, inducing passive circumferential confining pressure whose magnitude and distribution depend primarily on the reaming length. At short reaming lengths, the compression zone is narrow and confining pressure remains localized near the wedge tip, failing to establish a continuous effective confinement zone. Radial restraint on the anchor is insufficient, elevating the risk of interfacial slip and debonding. At medium reaming lengths, the compression is more uniformly distributed along the bevel, allowing the rock to form a complete and continuous circumferential confining zone that enhances shear resistance and debonding resistance while suppressing micro-crack propagation. When the reaming length becomes excessive, over-compression drives the surrounding rock into widespread plasticity, progressively degrading the confining effect. Deprived of a stable rigid load-bearing matrix, the anchor experiences a disordered stress state and compromised system performance.

Reaming length further governs the progression of plastic damage in the surrounding rock, which in turn dictates the failure mode and ductility of the anchoring system. At short reaming lengths, damage remains localized, and the anchor interface debonds abruptly under peak load—a distinctly brittle failure pattern. Under medium reaming length conditions, the damage in the surrounding rock is uniformly distributed without becoming interconnected, and the anchoring system exhibits ductile failure characteristics with synergistic bonding–interlocking cooperation, resulting in a higher residual bearing capacity. Under the 12 cm excessive reaming length condition, the plastic damage in the surrounding rock becomes extensively interconnected, and the anchoring system undergoes overall collaborative instability with the surrounding rock, leading to a substantial decline in long-term support reliability. Considering the combined effects of confining pressure, damage evolution, and structural ductility, the 10 cm reaming length achieves an optimal balance between anchoring bearing capacity and disturbance to the surrounding rock, offering the best overall engineering value.

5. Conclusion

1.Under the condition of a fixed 40° wedge-shaped reaming angle, the reaming length exhibits a pronounced three-stage regulatory characteristic on the stress state of the anchoring system. Through the coupled effects of four aspects—the formation degree of the composite load-bearing system, the stress level of the anchoring agent, the circumferential confining pressure constraint of the surrounding rock, and the evolution of plastic damage—the reaming length collectively influences the ultimate bolt anchoring force.

2.The anchoring force exhibits a three-stage evolution pattern with increasing reaming length: "stable low load — rapid growth — slow growth." The reaming length interval of 6–10 cm represents the most significant range for anchoring performance enhancement, with 10 cm identified as the optimal balance point between load-bearing efficiency and surrounding rock stability.

3.Based on the comprehensive analysis of ultimate stress distribution, surrounding rock plastic damage characteristics, and quantitative anchoring force results, the optimal reaming length for the 40° wedge-shaped reaming is determined to be 10 cm. In engineering practice, the reaming length interval of 8–10 cm is preferentially recommended as the standard construction parameter range.

4.This study establishes a quantitative description of the coupled relationship between the 40° wedge-shaped reaming length and anchorage performance, contributing to an improved parameter design framework for reaming anchorage technology. The results offer both theoretical guidance and quantitative data to support the optimization of reaming anchorage practices in deep soft-rock roadways.

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