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Study on Mechanical Mechanism and Pull-out Bearing Capacity of Cylindrical Reaming Anchorage

Aolong Liu*

School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo 454003, China
*Corresponding Author: Aolong Liu (Email: 2042543424@qq.com)

ABSTRACT

To address the engineering challenges of low anchorage capacity, easy shear debonding failure at the anchorage interface, and the difficult long-term stability control of the roof in deep coal mine soft-rock roadways, a refined 3D numerical model was established in Abaqus based on the bolt-adhesive-surrounding rock collaborative bearing theory and the interfacial shear transfer theory. The influence of cylindrical straight reaming diameter on bolt pull-out behavior was systematically investigated. Seven reaming diameters (24, 30, 40, 50, 60, 70, and 80 mm) were used to analyze the peak pull-out force, load evolution characteristics, stress distribution of the anchorage agent, interfacial load transfer characteristics, and the evolution of anchorage failure modes. Results show that the peak pull-out force exhibits a three-stage trend: rapid increase, slight decrease, and gradual rise with rising reaming diameter. At a 40 mm reaming diameter, the anchorage agent stress distribution is relatively uniform, local stress concentrations are low, and the collaborative bearing state is ideal, yielding a peak pull-out force of 143 kN, which can be used as a reasonable engineering reaming diameter. When the reaming diameter exceeds 50 mm, the effective bearing thickness of the surrounding rock is insufficient; the borehole wall rock gradually enters a plastic softening state; the effective shear capacity decreases; and the pull-out force declines. Within 60–80 mm, the gain from increased contact area compensates to some extent for the weakening of the surrounding rock, and the pull-out force continues to rise. However, surrounding rock damage is severe, construction costs increase significantly, and the engineering practical value is limited. This study can provide a sufficient theoretical basis and reference for mechanism analysis, parameter optimization, and engineering design of reaming bolt support.

KEYWORDS

Soft rock roadway; Roof support; Cylindrical reaming; Reaming anchorage; Collaborative bearing; Pull-out force; Anchorage agent stress; Numerical simulation.

1. INTRODUCTION

Coal mining in China has gradually extended to greater depths, and the number of deep, high-stress soft rock roadways continues to increase. Under complex deep geological conditions, the surrounding rock typically exhibits high in-situ stress, low strength, weak cementation, pronounced rheological behavior, and poor integrity. Thus, roof safety control has become a key technical issue affecting the safe and efficient production of mines [1, 2]. As a widely used active support in coal mine roadways, the anchorage system's stress stability and load-bearing reliability strongly influence the overall support effect and roadway safety [3, 4].

Conventional bolt anchorage primarily relies on bonding and friction at the anchorage agent-surrounding rock interface to transfer loads and diffuse stresses. In soft and broken surrounding rock, interfacial bonding strength is relatively low, and shear stress tends to concentrate heavily near the orifice, producing a steep stress gradient and highly uneven distribution. When the external load exceeds the interface's ultimate bearing capacity, sudden interfacial debonding may occur, leading to complete bolt pullout, which can further trigger accidents such as roof separation, local caving, and even large-scale instability, seriously threatening underground safety production [5, 6].

Reaming anchorage technology can increase the anchorage contact area, improve interfacial stress distribution, and form a certain extrusion-interlocking effect by presetting a reaming section in the bolt hole. It is conducive to improving the anchorage capacity and overall stability of the support system, showing obvious technical advantages and application potential in deep broken surrounding rock support [7, 8]. At present, relevant studies worldwide mostly focus on wedge-shaped reaming angle, reaming length, anchorage segment size, and anchorage material properties. Systematic research on the influence of the equal-diameter cylindrical straight reamer diameter on anchorage performance is relatively limited. In particular, the internal correlation among reaming diameter, anchorage agent stress, interfacial load transfer law, bearing capacity evolution, and failure mode transition has not been fully revealed [9, 11]. Engineering practice shows that when the reaming diameter is too small, the improvement of anchorage capacity is limited and difficult to meet soft rock support requirements; when the reaming diameter is too large, it may disturb the surrounding rock bearing structure, reduce borehole wall stability, increase construction difficulty and material consumption, and affect comprehensive economic benefits. Therefore, studying the reasonable reaming diameter of cylindrical reaming anchorage and revealing its bearing enhancement mechanism has important theoretical significance and engineering value.

Accordingly, taking the roof bolt support in deep coal mine soft rock roadways as the research background, this paper establishes a 3D numerical anchorage model under different reaming diameters using Abaqus. The influence of reaming diameter on bolt pull-out capacity, load-displacement characteristics, anchorage agent stress field, and failure mode is analyzed, and reasonable reaming parameters are discussed to provide support for scientific design and engineering application of reaming bolts in deep soft surrounding rock.

2. STRESS CHARACTERISTICS AND RESISTANCE-INCREASING MECHANISM OF CYLINDRICAL REAMING ANCHORAGE

2.1. Interfacial Stress Characteristics of Conventional Anchorage

Under tensile load, the axial force of the bolt is transferred to the anchorage agent through the bolt-anchorage agent interface, and then diffuses to the surrounding rock via the bonding and friction forces at the anchorage agent-surrounding rock interface. Interfacial shear stress usually distributes in a rapid attenuation pattern along the borehole depth, with relatively high stress concentration and large gradient near the orifice, resulting in a short effective bearing length. When the pull-out force exceeds the ultimate bonding strength of the interface, overall interfacial debonding tends to occur, leading to a rapid decrease in bearing capacity. The failure process is relatively sudden with weak residual bearing capacity, which is difficult to adapt to the large-deformation and high-stress support requirements of soft rock roadways.

2.2. Resistance-increasing Mechanism of Reaming Anchorage

Cylindrical reaming anchorage forms a diameter difference between the reaming section and the conventional borehole, which can improve the stress state and enhance the overall bearing performance of the anchorage system in many aspects:

Contact area gain effect: Reaming significantly increases the anchorage agent-surrounding rock contact area, helping to reduce the average interfacial shear stress and improve the overall shear resistance of the interface.

Stress distribution optimization effect: Shear stress distributes more uniformly along the anchorage section, which effectively alleviates local stress concentration at the orifice and delays the initiation and development of local failure.

Extrusion-interlocking resistance-increasing effect: After a certain interfacial slip occurs, radial extrusion and mechanical interlocking are generated between the anchorage agent and the surrounding rock in the reaming section. The internal stress distribution of the surrounding rock is changed to form additional resistance, which helps improve the ultimate and residual bearing capacities of the anchorage system.

Overall, reaming anchorage transforms the anchorage system from single interfacial bonding control to a collaborative bearing mode dominated by bonding, extrusion, and interlocking, which helps improve anchorage reliability and long-term stability in soft surrounding rock.

3. ESTABLISHMENT OF NUMERICAL MODEL

3.1. Geometric Parameters and Constraint Conditions

A 3D numerical anchorage model was established using Abaqus/Standard, fully considering the structure and contact relationship among the bolt, anchorage agent, surrounding rock, and reaming section. The main geometric parameters are as follows:

Surrounding rock: diameter 300 mm, height 30 mm, with fully fixed constraints at the bottom to restrict displacement and rotation;

Bolt: diameter 20 mm, length 300 mm, adopting a linear elastic constitutive model to simulate tensile deformation;

Anchorage hole: reference diameter 24 mm, depth 250 mm, consistent with conventional bolt drilling size;

Reaming section: length 100 mm, located in the middle of the anchorage segment, with diameters of 24, 30, 40, 50, 60, 70, and 80 mm;

Loading method: axial displacement load of 5 mm applied at the bolt top to simulate the standard laboratory pull-out test.

3.2. Element Type and Contact Assumption

The model was meshed with C3D10M quadratic tetrahedral elements with moderate density and high quality, meeting the requirements of calculation accuracy and convergence.

The following simplified assumptions were adopted in the simulation to better match the actual soft rock anchorage engineering:

1.Relative slip between the bolt and anchorage agent is ignored, assuming tight bonding and compatible deformation;

2.The failure behavior of the anchorage agent-surrounding rock interface is mainly considered, as it is the most common failure surface in soft rock anchorage.

3.Both the surrounding rock and the anchorage agent adopt the Mohr-Coulomb plastic yield criterion.

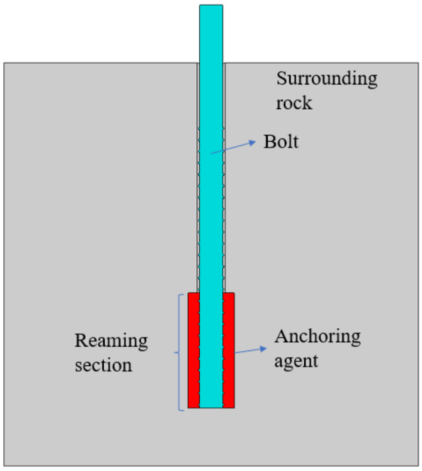

Figure 1. Schematic of Numerical Simulation Model

Fig. 1 shows the 3D numerical model of the bolt-anchorage agent-surrounding rock system. The model mainly consists of four parts: the surrounding rock, the central bolt, the anchorage agent filling body, and the middle reaming section. Fully fixed constraints are applied at the bottom of the surrounding rock to ensure boundary stability; axial displacement load is applied at the top of the bolt for uniform pull-out; the anchorage agent wraps the bolt and fills the gap between the bolt and borehole wall to ensure effective load transfer; the reaming section is located in the middle of the anchorage segment, forming an enlarged cylindrical cavity. This model can truly reflect the structural composition, contact relationship, and stress conditions of reaming anchorage, and effectively reveal its mechanical behavior.

4. ANALYSIS OF PULL-OUT BEARING CAPACITY AND ANCHORAGE AGENT STRESS

4.1. Influence of Reaming Diameter on Peak Pull-out Force

Fig. 2 shows the variation trend of peak bolt pull-out force with reaming diameter. The curve generally presents a three-stage characteristic: the pull-out force increases significantly from 24 mm to 40 mm, rising rapidly from 75 kN to 143 kN. In this stage, the increase of reaming diameter enlarges the anchorage contact area, effectively relieves interfacial stress concentration, gradually improves the collaborative bearing capacity between anchorage agent and surrounding rock, and presents a significant resistance-increasing effect. The bearing capacity reaches a high level near 40 mm, which is an excellent engineering state and can be regarded as a key parameter inflection point. At 50 mm, the pull-out force decreases to 124 kN, mainly because the further increase of reaming diameter leads to insufficient effective bearing thickness of surrounding rock, the borehole wall rock enters plastic softening state, the effective interfacial shear capacity decreases, and the reaming gain is partially offset by surrounding rock weakening. From 60 mm to 80 mm, the pull-out force rises gradually and finally reaches 163 kN. In this stage, the gain effect of continuous increase of contact area compensates the bearing capacity loss caused by surrounding rock weakening to a certain extent, but the surrounding rock damage degree is relatively high, and the engineering economy and safety are reduced. This trend comprehensively reflects the influence of reaming diameter on anchorage bearing capacity, and 40 mm has both bearing capacity advantage and engineering rationality.

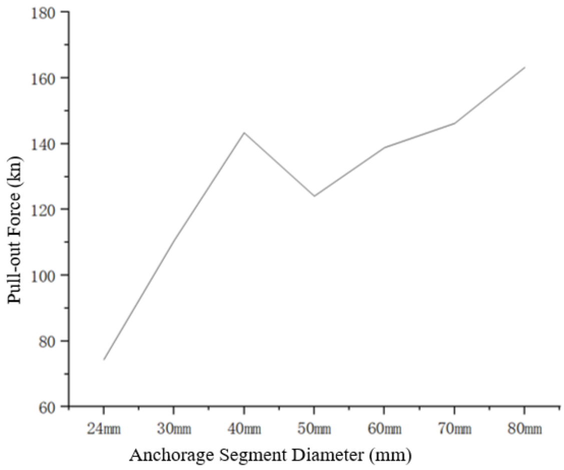

Figure 2. Relationship Curve Between Reaming Diameter and Peak Pull-out Force

4.2. Stress Distribution of Anchorage Agent

Fig. 3 shows the stress nephograms of the anchorage agent under different reaming diameters.

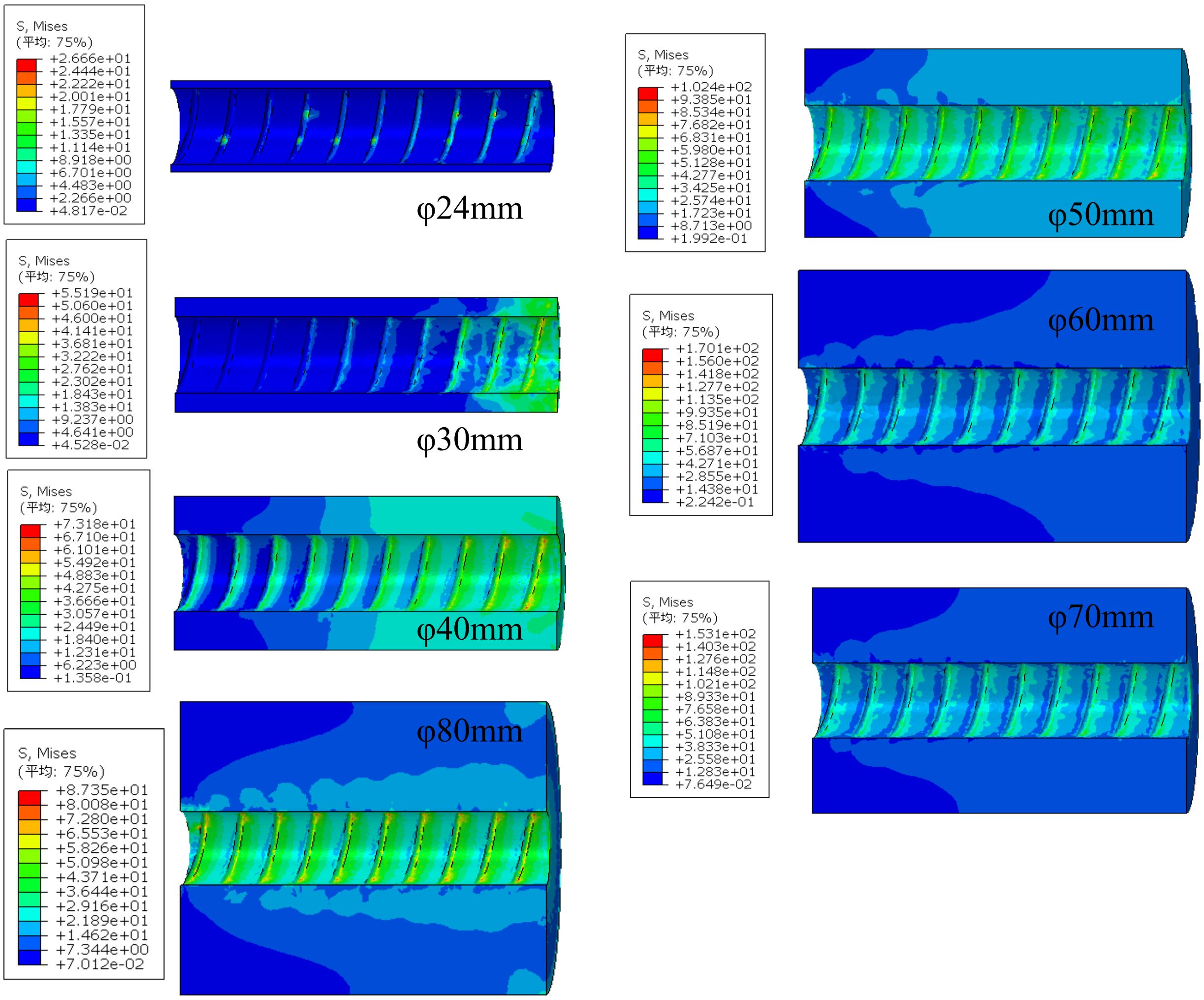

Figure 3. Stress Nephograms of Anchorage Agent Under Different Reaming Diameters

Fig. 3 presents the stress distribution characteristics of the anchorage agent corresponding to different reaming diameters. At 24 mm, the high-stress zone is mainly concentrated near the orifice, the stress in the deep anchorage agent is relatively small, the stress gradient is large, and local failure characteristics are obvious. At 30 mm, the high-stress zone expands to the middle of the anchorage section, the uniformity of stress distribution is improved, and local concentration is reduced. At 40 mm, the stress distributes relatively uniformly along the anchorage section without obvious local peaks; the stress state is ideal, and the collaborative bearing effect is prominent. At 50 mm, the overall stress level of the anchorage agent increases, the high-stress range expands, and the plasticity of the surrounding rock affects the stress of the anchorage agent. From 60 mm to 80 mm, the stress distribution tends to be gentle, the high-stress zone covers the entire length, but the stress level decreases, and stress diffusion is more sufficient.

With the increase of reaming diameter, the anchorage failure mode gradually evolves, which can well reflect the transformation of stress state and failure mechanism of the anchorage system: at 24 mm and 30 mm, orifice stress concentration is dominant, prone to local shear and sudden debonding failure with obvious brittle characteristics; at 40 mm, the interface stress is relatively uniform, dominated by overall collaborative shear, the failure process has certain ductility, and the bearing efficiency is high; at 50 mm, the influence of plastic softening of surrounding rock is obvious, the effective interface bearing capacity decreases, the failure is controlled by surrounding rock state, and the stability decreases; at 60–80 mm, contact area plays a dominant role, showing large-deformation overall bearing characteristics, with high theoretical bearing capacity but relatively large engineering risk and poor long-term stability. Based on the numerical simulation results, reaming diameter has significant effects on anchorage capacity, stress distribution, and failure mode. Comprehensive judgment from bearing performance, stress state, and engineering applicability shows that 40 mm cylindrical reaming can be used as a reasonable support parameter for deep soft rock roadways. Under this diameter, the stress distribution of the anchorage agent is uniform, the interface collaborative bearing state is good, the surrounding rock damage is low, and the construction difficulty is moderate. It can ensure a high anchorage force with good economy and reliability. For reaming of 50 mm and above, although the pull-out force can be further increased, the plastic damage of the surrounding rock is significantly aggravated, the borehole wall stability decreases, the construction cost increases significantly, and the comprehensive benefit is low. It is recommended to adopt cautiously under general engineering conditions.

5. CONCLUSIONS

Cylindrical reaming can transform the anchorage system into a collaborative bearing mode by increasing contact area, optimizing interfacial stress distribution, and forming a certain extrusion-interlocking effect, which is conducive to improving the anchorage capacity and stability of bolts in soft surrounding rock to a certain extent.

1. The peak pull-out force of the bolt generally shows a trend of rapid increase–slight decrease–gradual rise with the increase of reaming diameter. 40 mm reaming can be regarded as a reasonable engineering diameter, at which the pull-out force reaches 143 kN, the stress distribution of the anchorage agent and surrounding rock is relatively uniform, and local concentration is low.

2. Under 40 mm reaming, the collaborative deformation between anchorage agent and surrounding rock is relatively good, the overall shear failure is balanced, and the bearing efficiency and safety reserve of the anchorage system are relatively ideal, which is suitable for reaming support of deep soft rock roadways.

3. When the reaming diameter exceeds 50 mm, the influence of plastic softening of the surrounding rock increases and the pull-out force decreases; the recovery of bearing capacity at 60–80 mm mainly depends on the increase of contact area, the damage of the surrounding rock is aggravated, and the engineering practical value is relatively limited.

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