

Study on Rock-Breaking Efficiency and Adaptability of Wedge Tooth Cutters in Complex Formations

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Abstract

In composite strata, the excavation efficiency of tunnel boring machines (TBMs) is significantly influenced by the morphology of stratigraphic interfaces. This study employs the Abaqus explicit dynamics module to establish an interaction model between wedge-toothed cutterheads and composite strata, investigating the matching relationship between stratigraphic inclination (15°–60°) and cutterhead parameters (tooth diameter, tooth count, penetration resistance, rotational speed). Results indicate that the specific rock-cutting energy exhibits a V-shaped variation with stratum inclination, first decreasing and then increasing, with optimal efficiency at a 45° inclination. Stress fluctuations decrease by 18.9%, and rock is more prone to tensile-shear combined fracturing. Analysis of variance reveals penetration depth remains a highly significant factor, while the significance of tooth diameter and tooth count increases with inclination. Based on these findings, this study proposes a synergistic parameter optimization strategy: for low inclinations, a combination of small tooth diameter, high tooth count, low penetration rate, and medium rotation speed is recommended; for high inclinations, a combination of large tooth diameter, low tooth count, high penetration rate, and low rotation speed is preferred. This research provides a theoretical foundation for selecting TBM cutters and optimizing excavation parameters in complex geological formations.

Keywords

Wedge Tooth Cutter; Composite Formation; Formation Dip Angle; Rock Breaking Efficiency; Parameter Matching.

1. Introduction

As the core equipment in modern tunnel construction, the tunneling efficiency of tunnel boring machines (TBMs) directly impacts project costs and schedules. While TBMs maintain high and stable excavation performance in homogeneous rock strata, actual engineering projects often involve traversing composite formations where soft and hard rock strata alternate. The abrupt lithological changes at these stratigraphic interfaces subject cutterheads to severe dynamic impacts and eccentric loads, resulting in reduced rock-cutting efficiency, abnormal tool wear, and even fracture failure[1-4].

The stratigraphic dip angle between soft and hard strata serves as a critical geometric parameter that profoundly influences the interaction mechanism between cutterheads and rock mass. It is one of the core factors constraining TBM performance in composite strata. The harsh operating conditions and alternating loads in composite strata further exacerbate tool failure risks, making scientific cutter selection particularly crucial[5]. Compared to traditional

flat-edge tools, the Wedge Tooth Cutter demonstrates unique advantages. Research on their rock-breaking mechanisms and parameter optimization has become a hotspot, yielding significant progress. Research on rock-cutting mechanisms indicates that alloy teeth form dense cores upon rock penetration, with crack propagation predominantly exhibiting tensile characteristics[6-7]. Regarding tooth profile optimization, Huang et al.[8] discovered through numerical simulations that different tooth profiles yield varying rock-cutting efficiencies. Cheng C et al.[9] compared the cutting performance of flat teeth and spherical inserts under different rock conditions. Parameter influence studies systematically explored the effects of rotational speed, penetration rate, tooth count, and other factors on rock-breaking efficiency[10]. Additionally, Wu et al.[11] revealed that Wedge Tooth Cutter exhibits “progressive” rock-breaking characteristics with distinct periodic force variations. The rock-breaking mechanism and wear patterns of conical teeth have also been extensively studied[12-14].

Addressing abnormal tool damage in complex formations, researchers have explored multiple perspectives. Zhu et al.[15] elucidated the influence mechanism of lithological variations on tool abnormal damage. Hu et al.[16] and Brackmann et al.[17] explained the nucleation and propagation patterns of cracks under impact loads at the microscopic level. Jiang et al.[18] discovered through discrete element simulation that unbalanced torque at the interface can induce eccentricity and vibration. In exploring the mechanism of impact-induced tool damage, two primary perspectives exist regarding impact patterns at composite formation interfaces: one focuses on dynamic fluctuations in tool forces during the transition zone, specifically the rate of change in normal force[19-20]; the other emphasizes the phenomenon of peak normal forces at the interface, positing that these peaks cause impact overload damage[21]. Kang et al.[22] confirmed the abrupt increase in cutting forces at the formation boundary, while Wei et al.[23] developed a corresponding impact load calculation method.

Despite these substantial research achievements, studies on the synergistic matching relationship between the critical geometric parameter of formation inclination angle and cutter parameters remain insufficient. Particularly lacking are systematic theoretical guidance and experimental validation for optimizing the combination of cutter structural parameters and operating parameters under different inclination angle conditions. Therefore, this study employs a nonlinear finite element method to focus on the matching relationship between formation inclination and cutter parameters, providing a theoretical basis and engineering guidance for cutter selection and construction parameter optimization in complex formations during TBM operations.

2. Simulation Design of Rock Breaking Using a Wedge Tooth Cutter

2.1. Geometric Model Establishment

This study employs finite element numerical simulation methods to establish a simulation model of the interaction between a Wedge Tooth Cutter and composite strata using the Abaqus explicit dynamics analysis module. It systematically investigates the effects of composite strata dip angle and various parameters of the Wedge Tooth Cutter on rock breaking efficiency. Given the complex mechanical properties of rock, the linear Drucker-Prager yield criterion, suitable for analyzing rock materials, was employed to simulate the plastic constitutive relationship of rock. The rock material properties were assumed to be isotropic and homogeneous.

Since the cutter ring directly contacts the rock during actual breaking operations, a flat-tooth wedge tooth cutter model was developed using the commonly used cutter head model in engineering practice. Components like the hub and shaft were omitted, retaining only the critical cutter ring elements. The cutter ring diameter is 459 mm for the Wedge Tooth Cutter with a tooth height of 12 mm. The H13 steel used for the cutter has the following primary

parameters: density 7800 kg/m^3 , elastic modulus 210 GPa , Poisson's ratio 0.3 . The composite formation model dimensions are designed as $1000 \text{ mm} \times 300 \text{ mm} \times 100 \text{ mm}$, with sandstone on the left and granite on the right, connected by an inclined interface. The lithological parameters of the sandstone and granite are shown in Table 1. To comprehensively investigate the impact of stratigraphic inclination on the rock-breaking efficiency of the Wedge Tooth Cutter, this study established four typical stratigraphic inclination conditions: 15° , 30° , 45° , and 60° . This design effectively simulates the transition process of the cutter entering from soft rock to hard rock under real geological conditions. The rock-breaking model of the Wedge Tooth Cutter is shown in Fig. 1.

Table 1. Rock Material Parameters

Rock Formation	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)
Granite	2730	57	0.31	36.54
Sandstone	2400	38	0.25	21.38

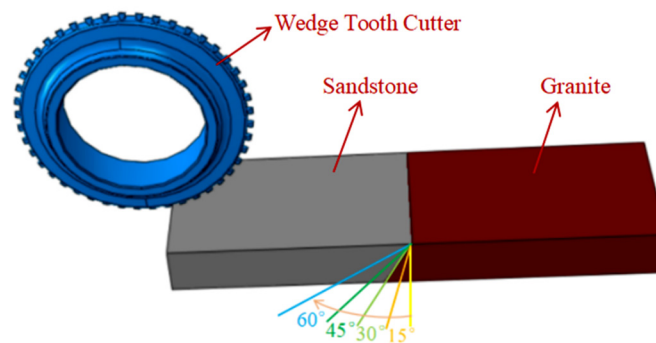


Fig 1. Simulation Model of Rock-Breaking with Wedge Tooth Cutter

2.2. Boundary Conditions and Mesh Generation

To more realistically simulate actual working conditions, the rock's base is fully constrained with 6 degrees of freedom. Non-reflective boundary conditions are applied to the rock's base and sides to prevent the rock's finite dimensions from influencing its fragmentation. Considering that the material of the Wedge Tooth Cutter is a rigid body, it is assigned horizontal translational motion and rotational motion about its own center of mass. The hob ring's movement speed is set to 0.4 m/s , and the cutterhead rotational speed is set to $1\text{-}4 \text{ r/min}$. This configuration enables the wedge tooth cutter to rotate around its center of mass while simultaneously cutting the rock along the horizontal plane. The alloy tips of the cutter teeth must penetrate the rock surface. An erosion-based surface-to-surface contact model was employed between the cutter and rock to better simulate the interaction process. The friction coefficient between the cutter and rock is set to 0.2 , ensuring residual elements maintain contact functionality after partial element failure and removal.

To enhance simulation accuracy and reduce computation time, the composite strata are meshed using hexahedral elements. The central contact region undergoes 1 mm mesh refinement, while the remainder receives simplified meshing, resulting in $338,800$ rock mesh elements. Considering the complex mounting structure of the Wedge Tooth Cutter and its rigid body definition, a tetrahedral mesh was employed for the cutter. Since mesh density does not affect simulation results, no refinement was necessary. The cutter mesh comprised $13,643$ elements.

2.3. Verification of Mesh Independence

The number and quality of grid cells in a simulation model are critical factors affecting computational accuracy. When grid density increases to a certain level, computational results tend to stabilize and no longer exhibit significant variation. Excessively high grid density leads to a dramatic increase in computational resource consumption, while low-quality grids may cause convergence difficulties and amplify computational errors. To mitigate the impact of mesh density on simulation outcomes, a mesh independence analysis was conducted on the critical zone of the composite formation (rock-cutting tool contact area). The same operating condition was simulated using mesh sizes ranging from 0.6 to 1.6 mm. As shown in Fig. 2, when the mesh size was refined from 1.6 mm to 1.0 mm, the average normal force exhibited significant variation (>5%). However, when refined from 1.0 mm to 0.6 mm, the force variation remained below 2%. Balancing computational accuracy and efficiency, a mesh size of 1.0 mm was ultimately selected for the refined region.

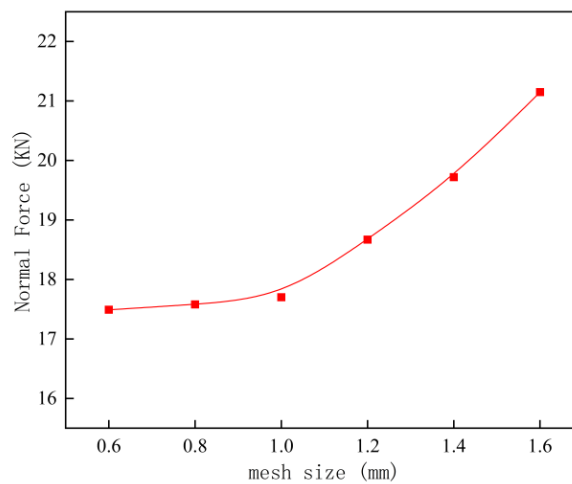


Fig 2. Grid-Independent Test Diagram

2.4. Simulation Parameter Settings

To analyze the differences in rock breaking performance of the Wedge Tooth Cutter under composite formations with varying inclinations, as well as the adaptability of structural and operational parameters for the Wedge Tooth Cutter in formations with different inclinations, thereby providing a reference for tool selection in field operations. Wedge Tooth Cutter conducted orthogonal experimental numerical simulations for four sets of parameters across four composite formations with varying stratigraphic inclinations. Each parameter set consisted of four levels, resulting in 64 rock-breaking simulations. The specific orthogonal experimental parameters are listed in Table 2.

Table 2. Simulation Parameter Settings

Factor	Level 1	Level 2	Level 3	Level 4
Tooth diameter (mm)	14	16	18	20
Number of teeth	30	35	40	45
Penetration (mm)	4	6	8	10
Rotational speed (r/min)	1	2	3	4

3. Simulation Results and Analysis

3.1. Analysis of Variance Based on Orthogonal Experiments

To quantitatively evaluate the significance of each parameter of the Wedge Tooth Cutter in influencing specific rock-breaking energy under different formation inclinations, this study conducted an analysis of variance on the results of 64 orthogonal experiments. This method decomposes the total variation in experimental data into variation attributable to individual factors and random error, subsequently using F-tests to determine the statistical significance of each factor's impact on the results. Table 3 presents the significance analysis results for each factor under different formation inclinations.

Table 3. Significance Analysis of Factors Affecting Rock-Breaking Specific Energy at Different Stratum Inclinations

rock dip angle	Tooth diameter	Number of teeth	Penetration	Rotational speed
15°	*	***	***	*
30°	**	**	***	--
45°	**	--	***	--
60°	***	**	***	**

Note: *** indicates highly significant ($P < 0.01$), ** indicates significant ($P < 0.05$), * indicates marginally significant ($P < 0.1$), -- indicates not significant ($P > 0.1$)*

Analysis results indicate: The significance of each factor's influence varies markedly across different inclination angles. Penetration proves a highly significant factor under all inclination conditions, confirming it as the most critical parameter affecting rock-breaking efficiency. The significance of tooth diameter increases with inclination angle, becoming highly significant at the steep 60° inclination. Tooth count exhibits high significance at low inclination angles but shows no significant effect at medium inclination angles. Rotational speed exhibits a certain influence at both small and large inclinations but is insignificant at medium inclinations. This finding provides a statistical basis for subsequent parameter optimization.

3.2. Dominant Effect of Rock Dip Angle

Rock dip angle is a crucial parameter characterizing the spatial orientation of geological bodies, defined as the angle between the inclination direction of stratigraphic planes and the vertical plane. This paper investigates the effects of varying rock dip angles on the rock-cutting force and efficiency during the rock-cutting process of TBM-mounted Wedge Tooth Cutter when the TBM excavation direction is parallel to the strike of composite strata. To visually demonstrate the effect of rock dip angle on the rock-cutting efficiency of the Wedge Tooth Cutter, numerical simulation tests were conducted with a fixed set of cutter parameters (tooth diameter 16 mm, number of teeth 40, penetration 10 mm, rotational speed 2 r/min). The output responses under different dip angles were analyzed.

3.2.1. Influence Patterns of Vertical Force and Rock-Breaking Efficiency

As shown in Fig. 3, when the rock dip angle increases from 15° to 60°, both the average normal force and the rock-breaking specific energy of the cutter head exhibit a “V-shaped” trend—first decreasing and then increasing with increasing rock dip angle. The minimum value occurs at a 45° rock dip angle, indicating the highest rock-breaking efficiency. At moderate inclinations, the cutter head more readily utilizes shear effects at interfaces to induce tensile-shear composite fractures in rock, enabling greater rock fragmentation with reduced force. Conversely, at low and high inclinations, the cutter head faces insufficient “sliding shear” and excessive “impact,” respectively, leading to diminished efficiency.

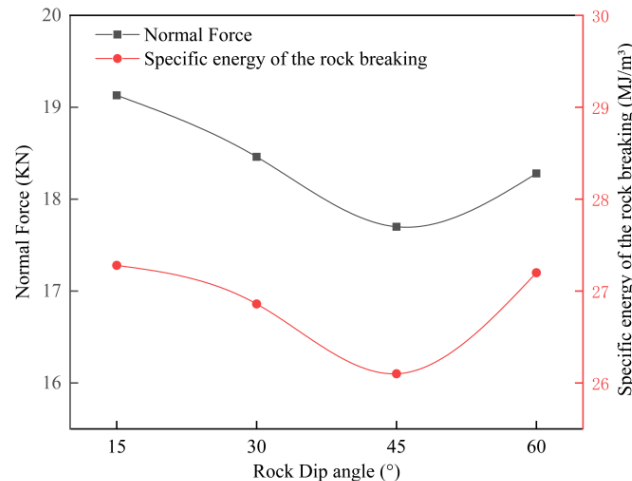


Fig 3. Effect of Rock Dip Angle on the Rock-Breaking Specific Energy and Vertical Force

3.2.2. Analysis of Mechanical Mechanisms

Based on fluctuations in the rock-breaking specific energy and rock-breaking force of the Wedge Tooth Cutter under varying rock dip angles, composite strata with different rock dip angles are classified into three types: those with rock dip angles less than 30° are classified as low-rock dip angle composite strata, those between 30° and 45° as medium-rock dip angle composite strata, and those greater than 45° as high-rock dip angle composite strata. To further elucidate the rock-breaking mechanisms under varying inclinations, the stress conditions experienced by rock units were extracted and analyzed, with their total volumes calculated as the rock fragmentation volume. Fig. 4 displays the equivalent stress distribution of rock under varying rock dip angles. It is evident that stress fluctuations differ across rock dip angles, leading to variations in the rock-breaking specific energy and rock-breaking force. The inclination magnification in the equivalent stress diagram reveals that stress fluctuations exhibit a decreasing-then-increasing trend. At a 45° rock dip angle, the stress fluctuations experienced by the cutter at the stratum boundary are minimal, reducing stress fluctuations by approximately 18.9% compared to both high-angle and low-angle composite strata. This demonstrates that variations in the rock-breaking specific energy and rock-breaking force are closely related to stress fluctuations experienced by the cutter head at different rock dip angles. The causes of stress fluctuations due to varying rock dip angles include the following aspects.

(1) Low-angle formations ($<30^\circ$): As shown in Fig. 4(a), the steep interface at this rock dip angle results in smaller rock fragmentation volumes. Upon initial contact with the interface, the cutter is prone to “sliding” or “bouncing” due to rigid support from the underlying granite, leading to unstable cutting. This impact load reduces effective fragmentation energy, converting part of the energy into useless work, thereby increasing stress fluctuations and raising the rock-breaking specific energy.

(2) Medium-inclination strata (30° – 45°): As shown in Fig. 4(b) and Fig. 4(c), this angle represents the “optimal angle.” Not only does it exhibit minimal stress fluctuations, but it also achieves the largest rock-breaking volume, with the rock-breaking specific energy reaching its minimum at 45° . When the cutter tooth tip contacts the interface, it most readily induces tensile cracks oriented toward the interface in sandstone while generating shear slip in granite. This “tension-shear composite” fracturing mode maximizes exploitation of the rock's inherent structural weak planes, facilitating large-volume fragmentation, reducing stress fluctuations, and achieving greater rock fragmentation volume with lower force.

(3) Rock dip angle ($>45^\circ$): As shown in Fig. 4(d), the dip interface is relatively gentle. During cutting, the cutter tip primarily compresses and shears the overlying sandstone. However, it also encounters a “supporting” effect from the underlying hard granite, requiring the cutter to

overcome greater resistance for effective penetration. Stress fluctuations increase accordingly, resulting in higher rock-breaking forces.

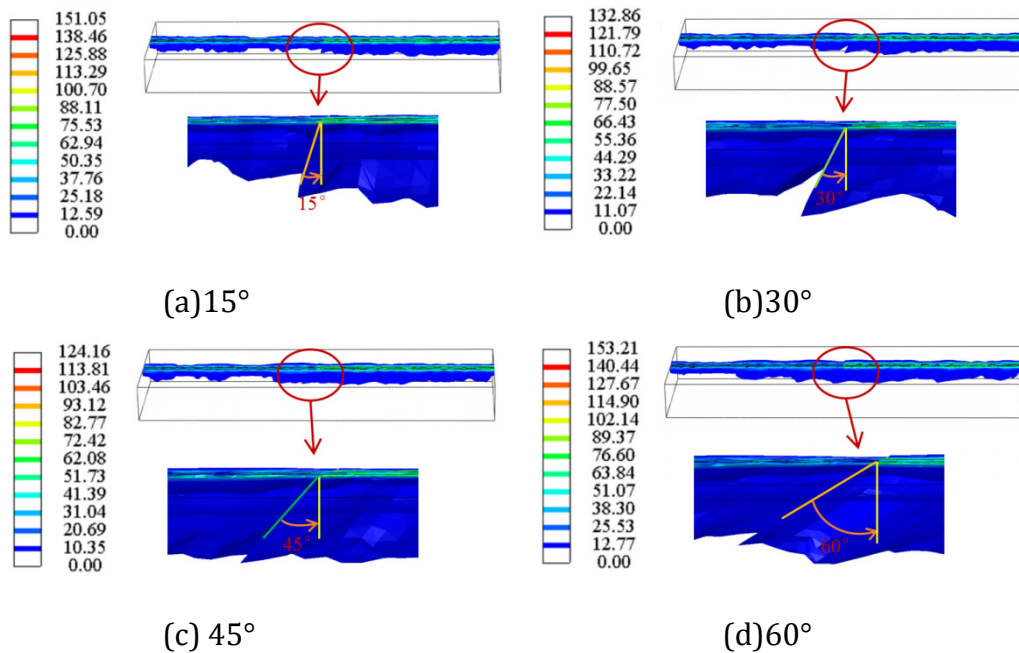


Fig 4. Equivalent Stress Diagram for Rock at Different Rock Dip Angles

3.3. Optimization Analysis of Hobbing Cutter Working Parameters Under Different Rock Dip Angles

The analysis above identifies a 45° rock dip angle as the optimal angle. However, in actual engineering practice, rock dip angle is a geological condition that cannot be altered. Furthermore, the variance analysis results indicate that the influence of cutter parameters on the rock-breaking specific energy is highly dependent on rock dip angle. Therefore, this section will combine the conclusions from the significance analysis with simulation data from all parameter combinations to explore in depth how adjusting these parameters can adapt to different rock dip angles, enabling the Wedge Tooth Cutter to achieve optimal rock-breaking efficiency under such stratum conditions.

3.3.1. Penetration Adaptability

Based on the significance analysis conclusions above, Penetration emerges as a core parameter exhibiting high significance ($P < 0.01$) across all inclination angles. Its optimization strategy undergoes a strategic shift with the inclination angle. As shown in Fig. 5, the selection of Penetration reveals a strategic inflection point determined by the rock dip angle. In low-inclination formations (15°), low Penetration (4–6 mm) is clearly the optimal choice, featuring lower specific rock-breaking energy. As penetration depth increases, the rock-breaking specific energy gradually rises. The rock-breaking specific energy at 10mm penetration depth is approximately 36.2% less efficient than at 4mm. This occurs because greater penetration depth at low inclinations increases the contact area between the cutter and granite, leading to substantial compressive resistance. However, in steeply inclined formations with a rock dip angle of 60°, with increased penetration, the rock-breaking specific energy decreases progressively, while rock-breaking efficiency gradually increases. The strategy must shift to employing high penetration values of 8-10 mm, resulting in a significant 28.0% reduction in the rock-breaking specific energy compared to the 4 mm low penetration. In medium-inclination formations around 45°, the rock-breaking specific energy at 8 mm penetration improves by 17.4% compared to the 10 mm operating condition. This clearly demonstrates that at high

inclinations, only high penetration depth can force the cutter to effectively engage hard rock, preventing energy waste on surface grinding.

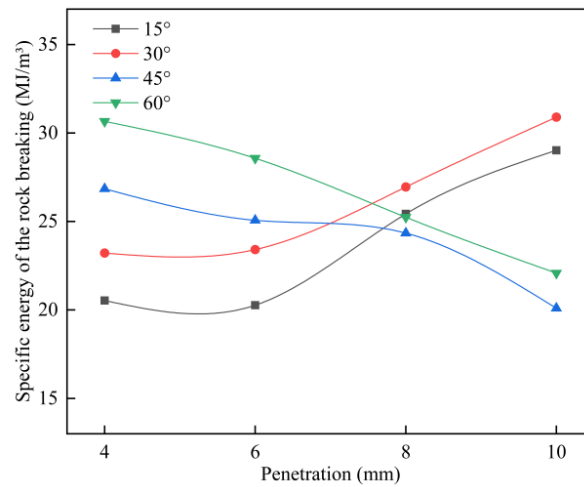


Fig 5. Relationship between penetration and the rock-breaking specific energy per unit work under different rock dip angles

3.3.2. Adaptability of Rotational Speed

The significance of rotational speed varies with operating conditions, necessitating targeted optimization. As shown in Fig. 6, for a 15° rock dip angle formation, the rock-breaking specific energy curve reaches its minimum at moderate rotational speeds (2–3 r/min). Increasing the speed from 3 rad/s to 4 rad/s at this point results in a rock-breaking specific energy increase of approximately 19.5%, attributed to heightened dynamic effects at high speeds that exacerbate ineffective slippage of the cutter. For medium-inclined rock dip angles at 45°, low rotational speeds (1-2 r/min) exhibit optimal efficiency. Increasing the speed to 4 rad/s causes the rock-breaking specific energy to surge by 24.5%, indicating that at this optimal crushing angle, sufficient contact time between the cutter and rock must be ensured to achieve large-volume fragmentation. For 60° high-inclination strata, the low rotational speed of 1 r/min is the optimal choice, with efficiency 10.0% higher than the 2 rad/s operating condition. This proves that at high-inclination interfaces, low rotational speed is key to suppressing slippage and maintaining cutting stability.

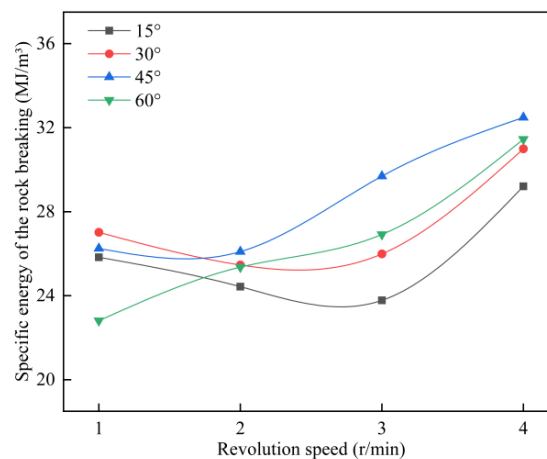


Fig 6. Relationship between rotational speed and the rock-breaking specific energy under different rock dip angles

3.4. Optimization Analysis of Roller Cutter Structural Parameters Under Different Rock Dip Angles

3.4.1. Tooth Count Adaptability

As shown in Fig. 7, the significance of tooth count and its optimization direction exhibits a clear “Crossover” effect. In low-inclination formations at a rock dip angle of 15°, the rock-breaking specific energy decreases with increasing tooth count, with multi-tooth configurations of 40–45 teeth achieving the highest efficiency. Compared to 30 teeth, efficiency improves by 21.1%, aligning with the “multi-tooth close-cutting” high-efficiency model in soft rock cutting. However, as the inclination angle increases, the influence of hard rock intensifies. In high-inclination formations at a rock dip angle of 60°, the situation completely reverses: configurations with fewer teeth (30–35 teeth) become optimal, achieving a 19.0% efficiency increase over 45 teeth. This occurs because, under impact loads, concentrating the load on fewer teeth to generate extremely high local stresses is a prerequisite for breaking hard rock. Excessive teeth only lead to load dispersion and reduced efficiency. At a moderate 45° rock dip angle, the 35-tooth configuration of the Wedge Tooth Cutter achieved the highest rock-breaking efficiency.

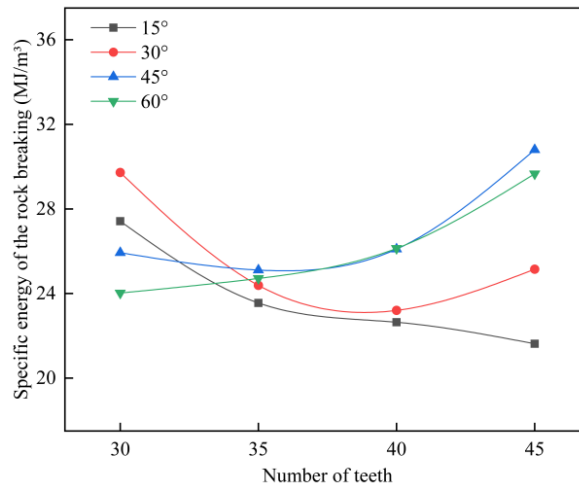


Fig 7. Relationship between Tooth Count and the Rock-Breaking Specific Energy per Unit Work under Different Rock Dip Angles

3.4.2. Tooth Diameter Compatibility

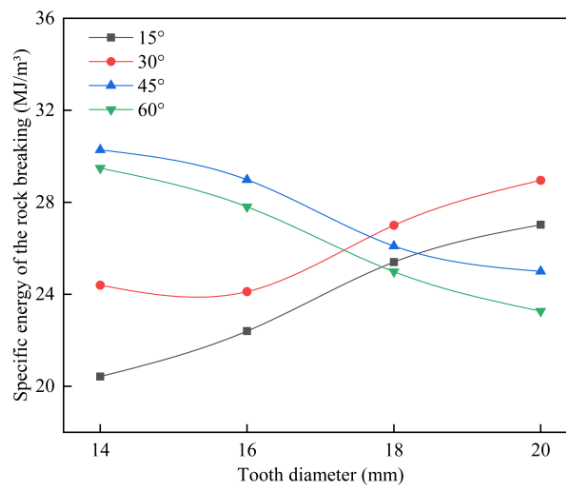


Fig 8. Relationship between tooth diameter and the rock-breaking specific energy under different rock dip angles

As shown in Fig. 8, the optimization strategy for tooth diameter is closely related to rock dip angle, with its significance systematically increasing as the dip angle grows. In low-angle formations (15°), the 14 mm small tooth diameter demonstrates clear advantages, with its rock-breaking specific energy 24.5% lower than that of the 20 mm large tooth diameter, highlighting the cutting efficiency of smaller teeth in soft rock. However, when inclination increases to 45° and 60° , the 20 mm large tooth diameter becomes the optimal choice. At a 45° medium inclination, the rock-breaking specific energy of the 20 mm tooth diameter decreased by 17.4% compared to the 14 mm; at a 60° inclination, this advantage expanded to 21.1%. The larger tooth diameter provides stronger structural impact resistance and more effective stress concentration capabilities under steep interfaces, forming the physical foundation for achieving efficient crushing of hard rock.

4. Conclusion

This study established a three-dimensional nonlinear finite element model for the interaction between the Wedge Tooth Cutter and composite strata using the Abaqus explicit dynamics module. Through orthogonal experiments incorporating four rock dip angles and four sets of cutter head parameters, it systematically simulated and revealed the rock-breaking behavior and parameter matching patterns under different operating conditions. Key conclusions are as follows:

- (1) Rock dip angle exerts a dominant influence on rock-breaking efficiency. As the rock dip angle increases from 15° to 60° , both the rock-breaking specific energy and average normal force exhibit a distinct “V-shaped” variation trend. Optimal rock-breaking efficiency is achieved at a 45° rock dip angle, where stress fluctuations are minimized, reducing energy consumption by approximately 18.9% compared to other inclination conditions. The rock fragmentation volume is maximized, facilitating the generation of tensile-shear composite fractures.
- (2) Analysis of variance indicates that penetration resistance is a highly significant factor ($P < 0.01$) under all inclination conditions, representing the most critical parameter affecting rock breaking efficiency. The significance of tooth diameter increases with inclination angle. Tooth count exhibits a significant influence at low inclinations but becomes insignificant at medium inclinations. Rotational speed shows moderate influence at both low and high inclinations.
- (3) Cutter operating parameters require dynamic optimization based on rock dip angle. Medium rotational speeds (2-3 r/min) combined with lower penetration (4-6 mm) are recommended for stable cutting in low-dip formations. Conversely, high-dip formations necessitate low rotational speeds (1 r/min) paired with high penetration (8-10 mm) to enhance load concentration and improve hard rock fragmentation efficiency.
- (4) The structural parameters of the cutter head should be synergistically matched with the rock dip angle. Under low-angle conditions, a design with a small tooth diameter (14 mm) and a high number of teeth (40-45 teeth) is recommended to enhance continuous cutting capability in soft rock; for steep-angle conditions, a configuration with a large tooth diameter (20 mm) and fewer teeth (30-35 teeth) is suitable, achieving effective hard rock fragmentation by increasing the load-bearing capacity per tooth.

This study systematically elucidates the rock-breaking mechanism of the Wedge Tooth Cutter in composite strata from the perspective of synergistic matching between “rock dip angle and cutterhead parameters.” It clarifies the adaptation patterns between structural parameters and operational parameters under varying inclination conditions, establishing an engineering-oriented parameter optimization strategy. The findings provide crucial theoretical foundations for TBM tool selection and excavation parameter optimization in complex geological formations.

Acknowledgments

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