

Study of Failure Mechanisms and Mechanical Responses in Double-borehole Splitting via Plunger-type Splitters across Different Lithologies

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Abstract. To study the influence of lithology on rock fragmentation during double-borehole splitting with a plunger-type splitter, the Discrete Element Method (DEM) was employed to simulate fracturing processes across various rock strengths. The results indicate that: (1) Rock splitting resistance enhances significantly with increasing strength, with the equivalent splitting force required for fragmentation rising from 329.2 kN for soft rock to 4316.1 kN for hard rock. Rock splitting resistance enhances significantly with increasing strength, with the equivalent splitting force required for fragmentation rising from 329.2 kN for soft rock to 4316.1 kN for hard rock. The force-displacement relationship transitions from a single-peak profile with a gradual slope in soft rock to a bimodal structure in medium-hard rock, eventually evolving into a multi-peak distribution in hard rock. This evolution is characterized by significantly higher pre-peak growth rates and accelerated post-peak strength declines. Correspondingly, the crack propagation rate rises substantially, with the expansion mode shifting from a slow, single-interval expansion to a rapid, multi-interval surge. (2) The double-borehole coalescence consistently forms a V-shaped fragmentation zone, characterized by a narrow loading side and a wide empty-borehole side. This failure mechanisms is dominated by macro-shear and follows a three-stage evolution: micro-crack initiation, main crack coalescence, and rock fragment spalling. The research results provide a theoretical basis for rock-breaking engineering under different geological conditions.

Keywords: Lithology; Double-borehole splitting; discrete element method; rock fragmentation; Failure mechanism.

1. Introduction

With the expansion of underground space development and mountainous infrastructure construction, blasting methods are increasingly restricted due to vibration disturbance concerns [1]. Hydraulic splitters have emerged as an effective means for the directional fragmentation of rock masses, owing to their advantages of low disturbance and high safety [2]. Specifically, double-borehole splitting which induces directional crack coalescence through the superposition of stress fields between boreholes is critical for creating free surfaces and achieving high rock-breaking efficiency.

Rock mechanical properties have been shown to influence rock fragmentation. Rock microstructure and elastic modulus directly determine the crack initiation stress threshold and fragmentation quality [3-5]. Rock brittleness is a core indicator for evaluating elastic energy accumulation and failure modes [6]. Furthermore, the failure of rock mass is influenced by structural anisotropy [7], and the combination of heterogeneous strata can significantly alter the instability and evolution laws around boreholes [8].

Regarding crack evolution, Bourne [9] and Wang et al. [10] defined the classification and formation sequence of cracks surrounding boreholes. Du et al. [11] and Ding et al. [12] explored the effects of borehole geometric on rock-bearing capacity and failure modes. Meanwhile, Han et al. [13] confirmed the controlling effect of the Geological Strength Index (GSI) on the distribution of the plastic zone around boreholes.

Existing research primarily focuses on the single-borehole splitting mechanism under specific lithological conditions. However, studies on the mechanical response and failure modes of double-borehole splitting across different rock strengths under the active loading of a plunger-type splitter remain scarce.

The Discrete Element Method (DEM) shows significant advantages in simulating rock damage evolution [14]. PFC2D, a representative DEM-based technology, can be utilized to investigate the influences of pre-existing defects, joint networks, and anisotropy on rock failure modes [15-18]. In this study, a double-borehole splitting numerical model employing a plunger-type splitter is established using PFC2D. By analyzing the equivalent splitting force and crack development characteristics, the influence of rock strength on rock-breaking mechanisms is elucidated. This work aims to provide a theoretical basis for static rock-breaking engineering under different geological conditions.

2. Numerical Simulation Design

2.1 PFC Method and Basic Assumptions

PFC2D characterizes the discontinuous mechanical behavior of rock masses by simulating the interactions within an assembly of rigid particles. The macroscopic brittle fracture of the material originates from the micro-scale evolution of particle bonds. To represent the high stiffness and brittle nature of the rock, the Parallel Bond Model (PBM) is employed. The elastic bonded domains formed by the PBM can simultaneously transmit both forces and moments. The contact forces at the bond, comprising the normal force (F_n) and the shear force (F_s) can be expressed as:

$$F_n = k_n \delta_n \quad (1)$$

$$F_s = k_s \delta_s \quad (2)$$

Where k_n and k_s represent the normal and shear stiffness; δ_n and δ_s denote the relative displacements in the corresponding directions.

To eliminate the interference of non-controlled variables and quantitatively analyze the isolated influence of rock strength on the rock fragmentation mechanism, the following simplified assumptions are established:

(1) The rock mass is considered a homogeneous and isotropic material at the macroscopic scale, neglecting the effects of natural joints.

(2) The differences between rocks of various strengths are characterized through the parallel bond micro-parameters.

(3) The numerical model adopts 2D plane strain conditions, disregarding the influence of the thickness direction.

(4) The loading process does not account for the effects of groundwater, temperature, or chemical interactions.

(5) Rigid wall constraints are applied to the model boundaries to simulate the confinement effect of the surrounding infinite rock mass.

2.2 Rock Strength Classification and Numerical Characterization Methods

To investigate the differences in mechanical response during the double-borehole splitting process under varying rock strength conditions, uniaxial compressive strength (UCS) was selected as the primary mechanical parameter to characterize rock strength, according to the rock strength classification standards [19]. The research objects were classified into three categories: hard rock, medium-hard rock, and soft rock, as shown in Table 1.

Table 1. Classification of rock hardness and corresponding UCS ranges

Rock Hardness	Hard Rock	Medium-hard Rock	Soft Rock
UCS (MPa)	UCS>60	60≥UCS>30	30≥UCS

In accordance with the aforementioned classification criteria for rock strength, distinct sets of parallel bond micro-parameters were assigned to soft, medium-hard, and hard rock specimens, respectively, as summarized in Table 2.

To eliminate the influence of particle structural parameters, identical particle system parameters were adopted for all numerical models, as listed in Table 3. By regulating the bond strength, the macroscopic characteristics are differentiated.

Table 2. Parallel bond micro-parameters for rocks with different strengths

Rock Hardness	Effective modulus (Pa)	Stiffness ratio	Tensile strength (MPa)	Cohesion strength (MPa)	Friction angle	Particle friction coefficient
Soft Rock	3.90×10^8	1.5	4.80	14.20	20	0.50
Medium-hard Rock	1.87×10^9	1.5	25.81	78.03	20	0.50
Hard Rock	8.06×10^9	1.5	58.21	166.73	20	0.50

Table 3. Basic geometric and physical parameters of the particle system

Parameter	Description	Value
n	Porosity (%)	15.5
R_{min}	Minimum particle radius (mm)	0.5
R_{max}/R_{min}	Particle size ratio	1.5
ρ	Density (kg/m ³)	1900
α_d	Local damping coefficient	0.7

2.3 Numerical Model Validation

Numerical uniaxial compression tests were conducted on rectangular specimens (50 mm×100 mm) under displacement-controlled loading to calibrate and validate the parameters defined in Section 2.2. The resulting stress-strain curves and associated failure modes are presented in Fig. 1.

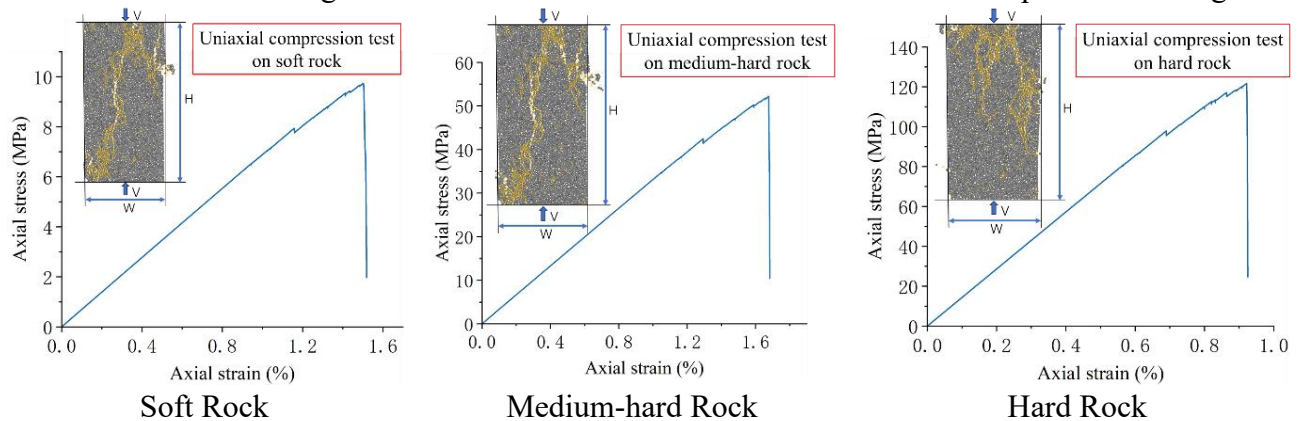


Fig. 1 Numerical stress-strain curves and final failure modes of rock specimens

As depicted in Fig. 1, all specimens exhibit a linear elastic response during the initial loading phase. Upon reaching the peak strength, a sudden stress drop is observed, reflecting typical brittle failure characteristics in the stress-strain response. The measured UCS for the soft, medium-hard, and hard rock models are 9.70 MPa, 52.02 MPa, and 120.20 MPa, respectively. These results align well with the rock strength categories, confirming that the selected micro-parameters accurately represent the macroscopic mechanical behaviors of rocks with varying strength.

2.4 Double-Borehole Splitting Numerical Test

To ensure comparability across different cases, the double-borehole splitting numerical tests (Fig. 2) were conducted using the same particle system parameters and contact model framework as defined in Section 2.2.

A 2D rock model (500 mm×500 mm) was constructed with a unit thickness of 1 m. Two boreholes with a diameter of 90 mm were symmetrically arranged at the center, maintaining a spacing of 40 mm.

Displacement boundary conditions were applied by utilizing rigid walls to fix the degrees of freedom of the model. This setup aims to restrict the overall rigid-body displacement of the rock mass, effectively leveraging the confinement of rigid boundaries to approximate the double-borehole splitting process within an infinite rock mass. The computational domain was expanded to approximately five times the borehole diameter to ensure that stress reflections from the rigid boundaries do not interfere with local crack evolution.

The plunger is simplified as a rigid wall located in the borehole. By applying a constant horizontal velocity to the rigid wall, the quasi-static loading of the splitter is simulated. The maximum displacement of the plunger is set at 18 mm, which meets the technical specifications of the actual splitting equipment.

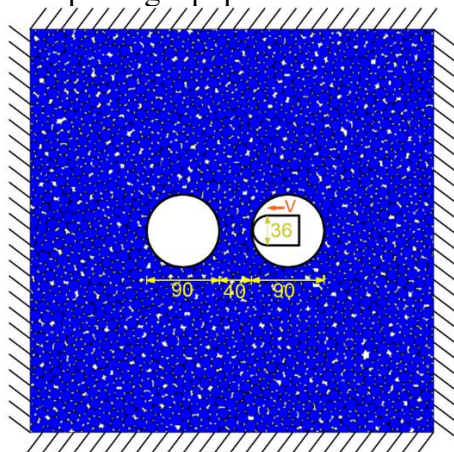


Fig. 2 Double-borehole splitting numerical test

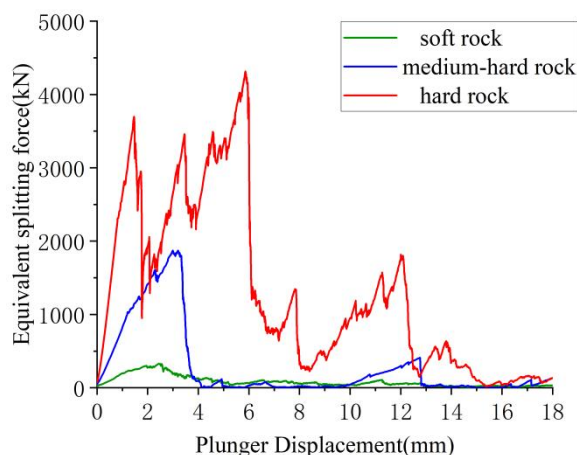


Fig. 3 Force-displacement curves across varying rock strengths

3. Results and Discussion

3.1 Mechanical Response of Double-borehole Splitting

The relationship between the equivalent splitting force and plunger displacement for different rock strengths during the double-borehole splitting process is illustrated in Fig. 3.

As illustrated in Fig. 3, under soft rock conditions, the equivalent splitting force exhibits a single-peak evolution with plunger displacement. The force reaches a peak of 329.2 kN at a displacement of 2.5 mm, with an average pre-peak growth rate of 131.7 kN/mm. Following the peak, the curve declines gradually at a rate of approximately 186.0 kN/mm. This gradual post-peak strength degradation is attributed to the low micro-bond strength characteristic of soft rock. During the failure process, the mechanical behavior is primarily dominated by frictional dissipation and particle rearrangement. Under this mechanism, the rock mass undergoes a progressive damage mode characterized by the steady expansion of micro-cracks, while brittle failure characteristics remain not pronounced.

In the medium-hard rock case, the curve exhibits a bimodal structure. The force rises sharply to a primary peak of 1871.4 kN at a displacement of 3.3 mm, with a post-peak drop rate of 3380.0 kN/mm—approximately 18 times that of soft rock. A secondary peak of 398.6 kN subsequently emerges at 12.6 mm. The characteristics of the primary peak reflect the substantial strain energy

accumulation and rapid release capacity (burst potential) of medium-hard rock, demonstrating typical brittle failure behavior. Meanwhile, the secondary peak corresponds to the residual strength fluctuations following the initial fragmentation of the rock mass.

Under hard rock conditions, the curve exhibits a distinct multi-peak distribution. Throughout the loading process, three prominent peaks with magnitudes exceeding 3000 kN are observed within the displacement intervals of 0~1.5 mm, 2~3.5 mm, and 5.5~6.0 mm, with peak values reaching 3685 kN, 3461 kN, and 4316 kN (the primary peak), respectively. The average pre-peak growth rate reaches 2085 kN/mm, which is 5 and 20 times that of medium-hard and soft rocks, respectively, highlighting the superior stiffness of the hard rock. Furthermore, the post-peak drop rate escalates to 13740 kN/mm—approximately 4 times that of medium-hard rock and 73 times that of soft rock. This drastic decline reflects the substantial strain energy accumulation and instantaneous release capacity of hard rock, characterizing a pronounced brittle failure mode.

3.2 Crack Evolution and Failure Mechanisms

To intuitively reveal the rock-breaking effects of double-borehole splitting across various rock strength, the fragmentation patterns and crack distributions at a splitter displacement of 18 mm for soft, medium-hard, and hard rocks are shown in Fig. 4.

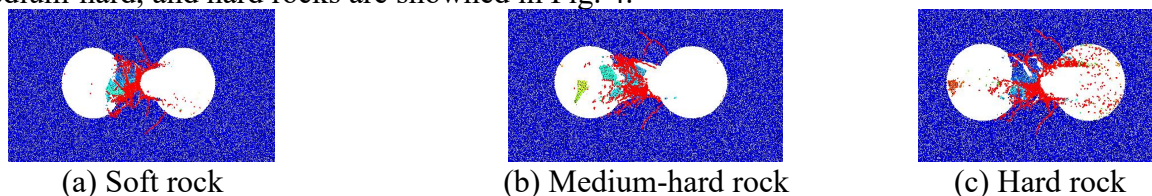


Fig. 4 Crack distributions at 18 mm plunger displacement for different rock strengths.

As illustrated in Fig. 4, when the displacement reaches 18 mm, all three cases achieve inter-hole coalescence, with the rock mass between the boreholes completely detaching. The macroscopic fracture zones consistently exhibit a distinct V-shaped feature (narrow at the loading side and wide at the empty-borehole side).

The double-borehole coalescence process can be divided into three stages: (1) the compressive action of the plunger induces longitudinal expansion under horizontal compression, leading to the initiation of micro-cracks; (2) under continued plunger advancement, these micro-cracks propagate and coalesce along the shear envelope, forming the V-shaped fragmentation zone; (3) as the plunger further advances, the surrounding rock mass undergoes additional failure, resulting in the spalling of fragmented rock from the empty-borehole side.

In the hard rock case, the stored elastic energy is released abruptly at the moment of inter-hole coalescence, triggering secondary micro-fractures and localized fragmentation flanking the primary V-shaped fragmentation zone.

The evolution of average crack count and crack propagation rates as a function of splitter displacement for different rock strengths are presented in Figs. 5 and 6.

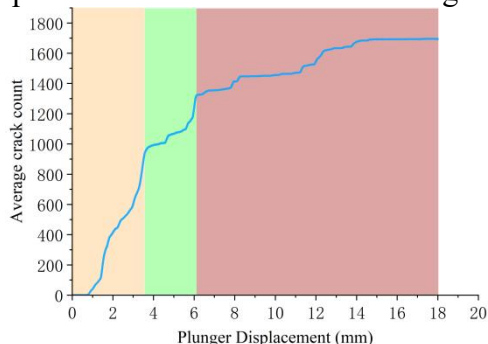


Fig. 5 Average crack count versus splitter displacement

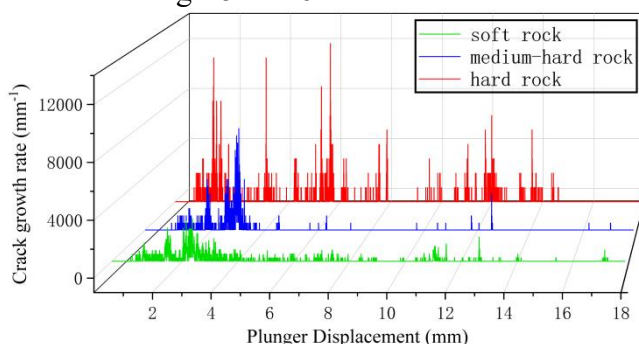


Fig. 6 Crack propagation rates versus splitter displacement under different rock strengths.

As shown in Fig. 5, the crack development process induced by double-borehole splitting exhibits distinct staged characteristics, following a three-stage law:

(1) Micro-crack initiation stage: This stage is characterized by the emergence of a substantial baseline of internal micro-cracks, with a mean count of approximately 1,000.

(2) Main crack coalescence stage: This period is predominantly driven by shear action, which governs the orientation and propagation of primary fractures. Notably, although the crack increment (averaging approximately 300) is lower than in the preceding stage, the propagation rate accelerates significantly due to the instantaneous formation and interconnection of the main fracture network.

(3) Rock fragment spalling stage: This final stage exhibits a smaller crack increment (averaging approximately 400) and a reduced growth rate, primarily stemming from sporadic localized damage during the detachment and ejection of fragmented rock mass.

As illustrated in Fig. 6, rock strength exerts a significant influence on the crack propagation rate:

(1) In the soft rock case, the maximum crack propagation rate is 3034 mm^{-1} . The intervals of higher propagation rates are concentrated between 1~3 mm, reflecting a relatively moderate evolution process.

(2) In the medium-hard rock case, the maximum crack propagation rate increases to 7595 mm^{-1} . The intervals of higher propagation rates are concentrated between 2~4 mm, exhibiting a noticeable lag compared to the soft rock and manifesting more pronounced brittle characteristics.

(3) In the hard rock case, the maximum crack propagation rate reaches as high as 12389 mm^{-1} (approximately four times that of soft rock). Unlike the previous cases, the response intervals are distributed across multiple stages (1~2 mm, 3~4 mm, 5~6 mm, and 12~13 mm), exhibiting a distinct multi-peak pattern with peak values of 11263 mm^{-1} , $10,136 \text{ mm}^{-1}$, $12,389 \text{ mm}^{-1}$, and $5,631 \text{ mm}^{-1}$, respectively. This characteristic multi-peak pattern manifests the explosive brittle failure of hard rock, where the abrupt liberation of elastic energy during coalescence drives localized fragmentation and secondary cracking flanking the primary V-shaped fragmentation zone.

4. Conclusions

Based on the investigation into the mechanical response, failure modes, and crack evolution of soft, medium-hard, and hard rocks during double-borehole splitting, the following conclusions are drawn:

(1) Rock strength significantly influences the evolution of the equivalent splitting force during the fragmentation process. As the rock strength increases from soft to hard, the required equivalent splitting force escalates from 329.2 kN to 4316.1 kN. The force-displacement relationship transitions from a gradual single-peak profile in soft rock to a bimodal structure in medium-hard rock, and ultimately evolves into a multi-peak distribution in hard rock. Furthermore, both the pre-peak growth rate and the post-peak drop rate increase markedly with rising rock strength.

(2) All three rock types exhibit a failure mode dominated by macro-shear. Upon double-borehole coalescence, a V-shaped fragmentation zone is consistently formed between the boreholes, characterized by a narrow width on the loading side and a wider expansion toward the empty-borehole side. The failure process follows a three-stage evolution: micro-crack initiation; main crack coalescence and formation of the V-shaped fragmentation zone.

(3) Crack development follows a three-stage evolution, with propagation rates strongly influenced by rock strength. The crack extension process progresses through three stages: micro-crack initiation, main crack coalescence, and localized damage accompanying rock fragment spalling. With increasing rock strength, the crack growth pattern evolves from a low-growth-rate, single-interval response to a high-growth-rate, multi-interval distribution. The unique high-growth, multi-interval pattern in hard rock reveals the underlying mechanism for the extensive secondary cracking observed around its V-shaped fragmentation zone.

Acknowledgements

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