

Dynamic response and damage mechanism of conglomerate under blasting loading

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Abstracts: To investigate the mechanical response and damage characteristics of conglomerate under blasting conditions, a theoretical computational model for conglomerate blasting zoning was proposed, grounded in the principles of multi-media wave dynamics and tailored to the structural properties of conglomerate. A mesoscopic numerical model for conglomerate blasting was developed, incorporating the matrix, gravel, and their cementation interfaces. Dynamic impact tests on conglomerate specimens were conducted using an electromagnetic split Hopkinson pressure bar (SHPB) system to validate the accuracy of the numerical model material parameters. Subsequently, single-hole blasting simulations were performed on conglomerate with varying explosive types and blast hole diameters, and the area of the crushed zone and crack distribution were quantitatively characterized. The results show that the effective stress in gravel exceeds that in the matrix under blasting loading, and the matrix around gravel is more prone to damage. With the increase in blast hole diameter and explosive performance, both the area of the crushed zone and the fractal dimension of cracks increase. However, when using low-performance explosives, the growth rate of the crushed zone area slows down as the diameter of the blast hole increases, while the growth rate of the fractal dimension of cracks accelerates. These findings can provide reference for gravel blasting engineering.

Keywords: conglomerate; blasting mechanism; mesoscopic finite element model; multi-media wave dynamics; dynamic response

1 Introduction

Conglomerate, also known as gravel-bearing sandstone, is a type of sedimentary rock composed of gravel (particles with a size of ≥ 2 mm), matrix materials, and cemented interfaces between them^[1]. At present, conglomerate-bearing mines have been widely discovered globally and possess great exploration potential^[2-3]. Illustrative examples include the Pilgrim's Rest gold mine in South Africa^[4], the Syama gold mine in southern Mali^[5], the rare earth mine in central and southern Africa^[6], the Kibali gold mine in the Democratic Republic of the Congo^[7], the oil mine in the Tarim Basin of China^[8], and the Husab mine in Namibia^[9], etc.

Influenced by the sedimentation process, conglomerate usually has complex compositions and structures. It is characterized by large differences in gravel sizes and uneven distribution, which result in strong heterogeneity of conglomerate^[10]. Researchers have carried out numerous studies on the mechanical properties of conglomerate, mainly focusing on the influence of gravel content and size on its mechanical properties and crack propagation^[11-14]. These studies have found

that the mechanical properties of conglomerate are significantly different from those of homogeneous rock masses, such as stress transfer, damage, and fracture patterns. Some scholars have also studied the influence of the mechanical property differences between the conglomerate matrix and gravel on crack propagation^[15], and the influence of particle shape on the elastic modulus of conglomerate^[16].

Due to the special structure of conglomerate, the mechanical response and failure mode of conglomerate under blasting are more complex. However, most of the existing research on the rock blasting zoning theory is carried out based on the assumption of homogeneity. The classical theory holds that the blasting zoning of rock is divided into a crushed zone, a fractured zone, and an elastic zone^[17-18]. Subsequent studies have attempted to improve this theory^[19-21], but none of them have deviated from the premise assumption of homogeneous rock masses. The existing blasting zoning theory models are more applicable to fine-grained rocks such as sandstone and shale, rather than conglomerate with prominent structural features.

As a convenient and economical method, numerical simulation is widely used to study the blast

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damage and fracture of rocks^[22–24]. Some studies have investigated the blast damage and fracture patterns of heterogeneous rock masses based on numerical simulation^[25–26]. However, most of these studies are based on ideal models, that is, the heterogeneous characteristics of the rock mass are set according to some simple rules, such as single cracks and layered rock masses. To address this limitation, mesoscale modeling techniques have been developed. Dong et al.^[27] established a polyhedral aggregate-based composite model using RFPA2D software, achieving excellent consistency between static compression simulations and theoretical predictions. Applying mesoscale modeling technology to the numerical modeling of heterogeneous rocks such as conglomerate is expected to achieve new breakthroughs.

Based on the wave dynamics of multiple media, a theoretical calculation model of conglomerate blasting partitioning was proposed for the structural characteristics of conglomerate. A mesoscopic numerical model of conglomerate blasting was developed using LS-DYNA numerical simulation software and Fortran programming, which includes the matrix, gravel, and their cementation interfaces. The blasting behavior of conglomerate under different explosive types and blast hole diameters is simulated. The irregular shape area recognition algorithm and fractal theory were used to quantitatively evaluate the degree of conglomerate crushing and crack propagation. This study can provide theoretical guidance for the formulation of blasting strategies in conglomerate mines.

2 Theoretical framework

Conventional blasting zoning models typically assume that the rock mass subjected to blasting behaves as a homogeneous material^[28–29], thereby oversimplifying the underlying physical processes. However, as a representative heterogeneous rock, conglomerate exhibits pronounced mechanical contrasts between the gravel clasts and the surrounding matrix, with the former demonstrating significantly higher strength properties. Moreover, the cemented interfaces between the gravel and the matrix induce reflection and transmission of stress waves, ultimately giving rise to complex failure patterns.

The multiphase medium wave propagation theory proposed by Holsapple^[30] and Schmidt et al.^[31] was originally developed to describe the propagation of stress waves induced by impact and explosion in multiphase media, such as porous or inclusion-bearing solid materials, with particular emphasis on the reflection, refraction, and energy transformation phenomena occurring at interfaces between different phases^[30–31]. As a typical multiphase medium composed of gravel and matrix, conglomerate exhibits pronounced

mechanical property contrasts and complex interfacial structures, enabling this theoretical framework to accurately characterize the evolution of explosive stress waves within such materials.

2.1 Distribution of explosive stress waves from detonation in conglomerate

Based on the blasting-induced damage processes in conglomerate and the multiphase medium wave propagation theory, this study proposes a novel blasting zoning model that explicitly accounts for the mesoscopic structural characteristics of conglomerate. The blast-affected domain is subdivided into four distinct regions: the crushed zone, the effective fracture zone, the fracture zone, and the elastic zone. The improved model provides a more accurate representation of the damage characteristics of conglomerate under explosive loading, as illustrated in Fig.1.

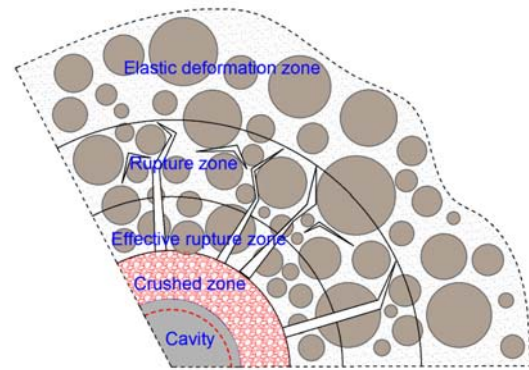


Fig. 1 Sketch of blasting zoning models for conglomerate

Based on the multiphase medium wave propagation theory and the characteristic propagation behavior of explosive stress waves, the evolution of stress waves within conglomerate can be expressed as follows^[30–32]:

$$\sigma_r(r) = P_0(r_0 / r)^n \exp[-\beta(r - r_0)] \quad (1)$$

$$\sigma_\theta(r) = k_t P_0(r_0 / r)^n \exp[-\beta(r - r_0)] \quad (2)$$

$$K_1^{\text{int}}(r) = \gamma T(r_0 / r)^p \exp[-\beta(r - r_0)] \quad (3)$$

where $\sigma_r(r)$ and $\sigma_\theta(r)$ denote the radial and tangential stresses at a distance r from the blast hole center, respectively; K_1^{int} represents the stress intensity factor at the crack tip along the interface, reflecting the driving force for interfacial crack propagation; P_0 is the peak initial shock pressure at the blast hole wall(MPa); r is the radial distance from the blast hole center(m); r_0 is the blast hole radius(m); n is the geometric attenuation exponent (typically ranging from 1.5 to 2.0); β is the material damping coefficient (m^{-1}); k_t is the tangential stress amplification factor; γ is the interfacial wave amplification factor; T is the peak tangential stress at

the interface (MPa); and p is the interfacial stress attenuation exponent.

2.2 Failure criteria and scope of damage in conglomerate under blasting loading

The rock in the crushed zone is regarded as an isotropic, incompressible, cohesionless granular medium, but there is still internal friction between the particles. The cohesionless Mohr-Coulomb strength criterion is used to determine whether the medium fails.

Then the radial stress in the crushed zone can be expressed as follows:

$$\sigma_r = \sigma_s \left(\frac{b_*}{r} \right)^{\frac{2 \sin \theta}{1 + \sin \theta}} \quad (4)$$

where σ_s is the dynamic compressive strength of rock under multi-axial stress condition, $\sigma_s =$

$[\sigma_c] \left(\frac{\rho_m C_p^2}{[\sigma_c]} \right)^{\frac{1}{4}}$; σ_c is the uniaxial compressive strength of rock; ρ_m is the rock density; C_p is the longitudinal wave velocity in the rock medium; θ is the internal friction angle of rock; and b_* is the radius of the crushed zone.

At the initial moment ($t=0$), the crushed zone initiates from the wall of the expanding cavity, where $a = b_* = r_b$, and r_b is the blast hole radius. Thus, on the wall of the expanding cavity ($r = a(t)$), there is

$$a_m^2 = 2 \frac{1+\nu}{E} \left(\xi^{1+1/h} L + \frac{1-h}{1+h} \right) [\sigma_c] b_{*m}^2 + \left\{ 1 - 2 \frac{1+\nu}{E} \left(\xi^{1+1/h} L + \frac{1-h}{1+h} \right) [\sigma_c] \right\} r_b^2 \quad (5)$$

where ν is Poisson's ratio of the rock; E is the elastic modulus of the rock; $\xi = b_*/a$; L is the strength coefficient associated with the internal friction angle of the rock; h is the coefficient of dilatancy characteristic, $h = \sin \theta$; b_{*m} is the maximum radius of the crushed zone; and a_m is the maximum radius of the expanded cavity.

Let $K = 2 \frac{1+\nu}{E} \left(\xi^{1+1/h} L + \frac{1-h}{1+h} \right) [\sigma_c]$, for the case

with significant cavity expansion, $(1-1/K) (a_m / r_b)^{-2} \approx 0$, equation (5) can be simplified as

$$b_{*m} = a_m K^{-1/2} \quad (6)$$

In the subsequent expansion of the expanding cavity, the blast hole pressure can be determined by the two-stage Jones-Miller adiabatic equation^[18].

At $r = a_m$, there is $\sigma_r = p_m$, i.e.,

$$p_m = \sigma_s \left(\frac{b_{*m}}{a_m} \right)^{\frac{2 \sin \theta}{1 + \sin \theta}} \quad (7)$$

By combining Equations (6) and (7), we obtain:

$$\sigma_s \left[1/K + (1-1/K) \left(\frac{a_m}{r_b} \right)^{-2} \right]^{\frac{\sin \theta}{1 + \sin \theta}} = \begin{cases} P_0 \left(\frac{a_m}{r_b} \right)^{-2\gamma_1} & a_m \leq r_k \\ P_0 \left(\frac{a_m}{r_b} \right)^{-2\gamma_2} \left(\frac{r_b}{r_k} \right)^{2(\gamma_1 - \gamma_2)} & a_m > r_k \end{cases} \quad (8)$$

where γ_1 is the adiabatic expansion index of detonation gas in the high-pressure stage; γ_2 is the adiabatic expansion index of detonation gas in the low-pressure stage; and r_k is the critical cavity radius at which the expansion state of detonation gas transitions.

From Equation (8), the ratio of the maximum expanding cavity radius to the blast hole radius a_m / r_b can be obtained. Substituting it into Equation (6), the range of the crushed zone b_{*m} / r_b can be derived.

By combining Equations (6), (7), and (8), the formula for the radius of the crushed zone under the initiation condition of columnar charge is obtained $R_c = b_{*m}$:

$$b_{*m} = \begin{cases} r_b \left(\frac{P_0}{\sigma_s} K^{\frac{\sin \theta}{1 + \sin \theta}} \right)^{\frac{1}{2\gamma_1}} K^{-1/2} & a_m \leq r_k \\ r_b \left(\frac{P_0}{\sigma_s} K^{\frac{\sin \theta}{1 + \sin \theta}} \right)^{\frac{1}{2\gamma_2}} \left(\frac{r_b}{r_k} \right)^{\frac{\gamma_1 - \gamma_2}{\gamma_2}} K^{-1/2} & a_m > r_k \end{cases} \quad (9)$$

It can be seen from Formulas (4), (5), (7), and (9) that the radius of the crushed zone is mainly affected by the following factors: rock properties, including dynamic compressive strength σ_c , dynamic tensile strength σ_t , elastic modulus E , Poisson's ratio ν , dilatancy characteristic h ; blast hole pressure P_0 , which is related to the density of explosive ρ_0 , detonation velocity D , and blast hole radius r_b ; and charging structure.

As the distance from the blast hole increases, the intensity of the stress wave attenuates. At this stage, the radial stress falls below the dynamic compressive strength of the gravel clasts but remains higher than that of the matrix, while the tangential stress exceeds the dynamic tensile strength of the gravel. Consequently, the matrix continues to undergo compressive failure, and the gravel clasts experience tensile damage. The failure criterion for this stage can be expressed as

$$\max[\sigma_r(r) - \sigma_{cd}^m, \sigma_\theta(r) - \sigma_{td}^g] = \sigma_c f \geq 0 \quad (10)$$

Substituting equation (10) into equations (1) and (2) yields the extent of the effective fracture zone:

$$R_f = r_0 (k_t P_0 / \sigma_{ef})^{(1/n)} \exp[\beta(R_f - r_0) / n] \quad (11)$$

At this stage, the tangential stress wave intensity is lower than the dynamic tensile strength of the gravel clasts but exceeds the dynamic tensile strength of the matrix material. Consequently, cracks initially develop within the matrix under the action of the stress wave. As the distance further increases, the stress wave intensity decays to a lower level that is insufficient to induce continued cracking of the matrix. However, due to the pronounced differences in elastic modulus, density, and wave velocity between the gravel clasts and the matrix, a significant impedance mismatch exists at the cemented interfaces. When the explosive stress wave propagates to the gravel–matrix interface, strong reflection and transmission phenomena occur. Under these conditions, the stress intensity factor at the interface crack tip, $K_I^{\text{int}}(r)$, surpasses the fracture toughness K_{IC}^{int} [33–34], leading to sustained interfacial cracking in the distal zone. The failure criterion for this stage can be expressed as follows:

$$\max[\sigma_\theta(r) - \sigma_{td}^m, K_I^{\text{int}}(r) - K_{IC}^{\text{int}}] \geq 0 \quad (12)$$

where: σ_{td}^m is the dynamic tensile strength of the matrix.

Substituting equation (12) into equations (2) and (3) respectively yields the corresponding fracture zone radii R_θ and R_K :

$$R_\theta = r_0 (k_t P_0 / \sigma_{td}^m)^{(1/n)} \exp[\beta(R_\theta - r_0) / n] \quad (13)$$

$$R_K = r_0 (\gamma T / K_{IC}^{\text{int}})^{(1/p)} \exp[\beta(R_K - r_0) / p] \quad (14)$$

$$R_{if} = \max(R_\theta, R_K) \quad (15)$$

When the intensity of the stress wave is insufficient to provoke failure either within the matrix or along the interfaces, this region is defined as the elastic zone:

$$r \geq R_{if} \quad (16)$$

3 Numerical simulation

3.1 Numerical models and programs

Conglomerate is a typical heterogeneous rock mass, characterized by a large number of randomly distributed gravel clasts embedded within a finer-grained matrix, resulting in complex internal interfaces. The boundaries between the clasts and the matrix form intricate interfacial zones where blast-induced stress waves undergo significant reflection and transmission. Modeling such a material as

homogeneous leads to substantial deviations from experimental observations. Therefore, a more precise and physically representative model is required to accurately simulate the mechanical behavior of conglomerate under blast loading conditions.

To simplify the modeling process, gravel clasts are idealized as circular shapes in this study. This geometric simplification preserves the essential characteristic of randomly distributed clast sizes and positions in calcareous conglomerate, thus ensuring the validity of the modeling approach. Based on the Monte Carlo random sampling method, gravel clasts are generated within a predefined spatial domain, in descending order of diameter. Except for the first clast, each subsequently generated clast is tested for overlap; if intrusion is detected, the clast is rejected and regenerated. For each successfully placed clast, its volume is accumulated until the target volume fraction is reached. The diameters and center coordinates of all accepted clasts are then exported into an array file.

The mesoscopic structure of the conglomerate is projected onto a uniform finite element mesh using the background grid projection method. Elements are identified and classified based on whether they belong to gravel, matrix, or cemented interface zones. Different material properties are then assigned accordingly, enabling the numerical model to capture the heterogeneous mechanical behavior of conglomerate rock.

Based on LS-DYNA and custom Fortran routines, a total of 3 070 gravel clasts were randomly embedded into a homogeneous finite element model. The model comprises three distinct material phases: gravel, cemented interfaces, and matrix. The modeling workflow is illustrated in Fig.2. Cemented interfaces were explicitly defined to characterize the bonding behavior between gravel clasts and the surrounding matrix. The full 3D model consists of approximately 2.74 million elements, with overall dimensions of

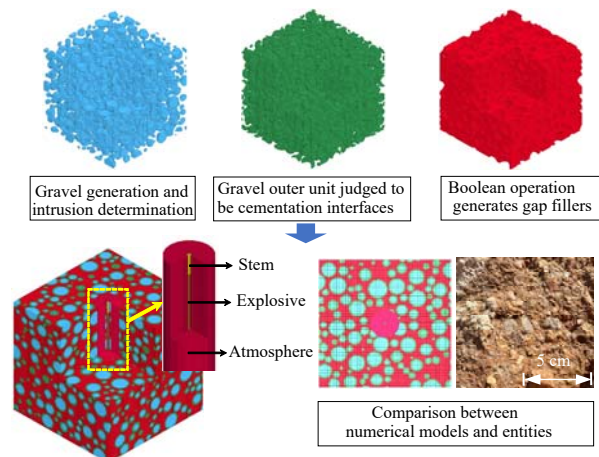


Fig. 2 Modeling process

100.0 mm × 100.0 mm × 100.0 mm. The blast hole has a diameter of 2.0 mm, with a stemming length of 10.0 mm and an explosive charge length of 65.0 mm. A fluid-structure interaction (FSI) algorithm was employed to perform the numerical simulation. To minimize boundary effects, the top surface of the model was defined as a free surface, while all remaining boundaries were treated with non-reflecting (absorbing) boundary conditions.

When rock blasting performance is suboptimal, standard engineering measures typically involve increasing the explosive charge or switching to a different explosive type^[35]. To investigate the influence of explosive type and charge on the blasting behavior of conglomerate, this study conducted numerical simulations using three types of explosives: TNT, No. 2 rock emulsion explosive, and a low-density explosive. These explosives were selected based on the availability of well-calibrated input parameters and the marked differences in their detonation velocities and brisance characteristics. Specifically, TNT is categorized as a high-brisance explosive, No. 2 rock emulsion represents a conventional explosive, and the low-density explosive is classified as a low-energy formulation. The simulation setup and test matrix are summarized in Table 1.

Table 1 Numerical simulation program

Number	Type of explosives	Hole diameter /mm
T-15	TNT	1.5
T-20	TNT	2.0
T-25	TNT	2.5
R-15	Rock emulsion explosive No. 2	1.5
R-20	Rock emulsion explosive No. 2	2.0
R-25	Rock emulsion explosive No. 2	2.5
D-15	Low density explosive	1.5
D-20	Low density explosive	2.0
D-25	Low density explosive	2.5

3.2 Parameter calibration

Accurately replicating the macroscopic rock mechanical behavior of conglomerate hinges on the precise calibration of the mesoscopic parameters of gravel and matrix. In the mesoscopic numerical simulation using the finite element method (FEM),

there is no direct correlation between macroscopic and mesoscopic parameters. Therefore, the calibration can only be accomplished through the trial and error method. Nevertheless, the conventional trial and error method has obvious drawbacks, including non-uniqueness in the parameter solutions, and the inefficient calibration performance.

To tackle these challenges, this study adopted the parameter calibration procedure developed by Pan et al.^[36]. This procedure provides a more efficient approach for optimizing mesoscopic parameters. Specifically, in this iterative process, the mesoscopic parameters were adjusted, and the output results from the simulation were compared with the experimental data until a satisfactory match between them was achieved.

The Riedel-Hiermaier-Thoma (RHT) model employs three independent strength surfaces to describe the material strength and damage evolution mechanism. It uses a state equation to characterize the relationship between material pressure and volumetric strain, enabling accurate simulation of the mechanical behavior of rock. Therefore, the RHT model was selected to simulate the elastoplastic damage behavior of gravel. The Karagozian & Case concrete (K&C) model accounts for material damage effects and elastoplastic behavior; this material model only requires compressive strength and density as direct input parameters, while other parameters and the state equation are automatically generated^[37]. In this study, the K&C model was used to characterize the mechanical properties of the matrix and cemented interfaces. The conglomerate studied in this research is mainly composed of gravel with granite composition and a matrix consisting of coarse-grained weakly cemented sandstone. Consequently, the mechanical parameters of granite were adopted as the initial parameters for gravel calibration^[38], and the parameters of coarse-grained weakly cemented sandstone were used as the initial parameters for filling (matrix) calibration^[39]. The calibrated constitutive model parameters for each component of the conglomerate are presented in Table 2 and Table 3.

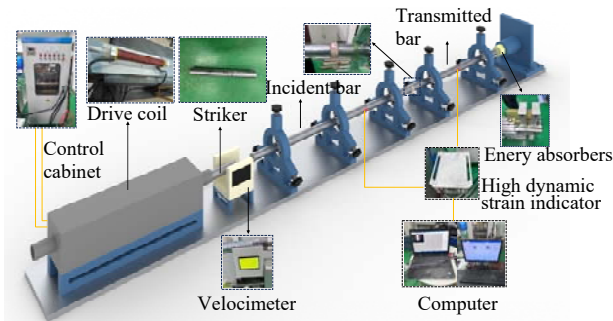
Table 2 Gravel RHT constitutive model parameters

Parameter	Value	Parameter	Value
Density ρ_0 / (g · cm ⁻³)	2.66	Failure surface parameter A	2.5
Compressive strength f_c / MPa	167.80	Failure surface parameter N	0.85
Tensile strength ratio f_t^*	0.1	Tension and shear meridian Q_0	0.72
Shear strength ratio f_s^*	0.12	Lode angle coefficient B	0.01
Shear modulus G / GPa	16.48	Reference compressive strain rate $\dot{\epsilon}_0^c$ / s ⁻¹	3 × 10 ⁻⁵
Compressive yield surface parameter g_c^*	0.85	Reference tensile strain rate $\dot{\epsilon}_0^t$ / s ⁻¹	3 × 10 ⁻⁶
Tensile yield surface parameter g_t^*	0.4	Fracture compressive strain rate $\dot{\epsilon}^c$ / s ⁻¹	50
Shear model reduction factor ξ	0.25	Fracture tensile strain rate $\dot{\epsilon}^t$ / s ⁻¹	45
Damage factor D_1	0.02	Compressive strain rate factor β_c	0.025
Damage factor D_2	1	Tensile strain rate factor β_t	0.045
Minimum damage strain ϵ_m^p	0.01	Damage pressure p_{cl} / MPa	112
Residual surface parameter A_r	2.5	Compaction pressure p_{co} / GPa	6
Residual surface parameter n_r	0.85		

Table 3 Cementation interface and matrix K & C constitutive model parameters

Material type	Densities ρ /($\text{g} \cdot \text{cm}^{-3}$)	Compressive strength σ_c /MPa	Young's modulus E /GPa	Poisson's ratio ν
Matrix	2.14	35.0	13.4	0.23
Cemented interface	2.14	28.0	10.7	0.23

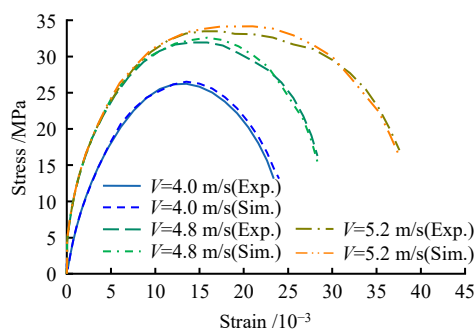
Dynamic impact tests on conglomerate were conducted using an electromagnetic split Hopkinson pressure bar (SHPB) system, with the experimental procedure illustrated in Fig.3. Concurrently, a mesoscale numerical model of the SHPB test for conglomerate was established in ANSYS/LS-DYNA, maintaining identical bar system parameters to the experimental setup (density: 7 850 kg/m³, elastic modulus: 210 GPa, Poisson's ratio: 0.3). The experimentally measured incident stress-time curve was applied to the impact surface of the incident

**Fig. 3** Electromagnetic SHPB test system

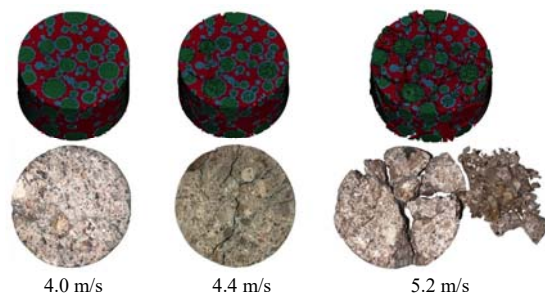
bar to simulate projectile loading. The distal end of the transmission bar was demoscoped as a non-reflective boundary to eliminate reflections of the transmitted stress wave, thereby ensuring simulation accuracy.

Figure 4 presents the comparison of dynamic stress-strain curves and failure modes at different impact velocities (V) obtained from numerical simulations and experiments. From the figure, it can be observed that the peak stress and peak strain of the experimental and simulated curves are basically the same. However, there are certain differences between the curves after the peak. This is because, in the simulation, damage is achieved by removing failed elements. As a result, there are certain differences in the manifestation form compared with the experiment.

Overall, the experimental curves and the simulated curves fit well. The failure modes of the specimens are relatively consistent, all being tensile failures. This indicates that the selected mesoscopic parameters of the conglomerate are effective and feasible.



(a) Stress-strain curves



(b) Failure characteristics

Fig. 4 Comparison between simulation and experimental results

The explosives were simulated using the *MAT_HIGH_EXPLOSIVE_BURN material model, and the equation of state is chosen from *EOS_JWL^[40], whose expression is

$$p_j = A_j \left(1 - \frac{\omega}{R_1 V_a} \right) e^{-R_1 V_a} + B_j \left(1 - \frac{\omega}{R_2 V_a} \right) e^{-R_2 V_a} + \frac{\omega E_0}{V_a} \quad (17)$$

where p_j is explosive gas pressure(MPa); V_a is relative volume (m³); E_0 is initial internal energy ratio of bombardment product (GPa); A_j , B_j , R_1 , and R_2 are experimentally determined constant. The relevant parameters are listed in Table 4, where D is burst speed, and p_{CJ} is Chapman-Jouguet pressure.

Table 4 Parameters of different types of explosives^[41-43]

Type of explosives	ρ /(kg · m ⁻³)	D /(m · s ⁻¹)	E_0 /(J · kg ⁻¹)	p_{CJ} /GPa	A_j /GPa	B_j /GPa	R_1	R_2
TNT	1 630	6 930	7.0×10^6	21.15	371.0	3.2	5.10	1.50
Rock emulsion explosive No. 2	1 150	4 000	4.2×10^6	9.70	214.4	1.8	4.20	0.90
Low density explosive	950	2 600	3.5×10^6	2.90	146.1	1.0	3.91	0.92

3.3 Simulation results

3.3.1 Evolution law of explosion stress waves

To comprehensively characterize the damage and fracture behavior induced by blasting in conglomerate rock, and concurrently to develop a numerical model for blasting in homogeneous rock, parameters specific

to conglomerate were incorporated into the rock model. The geometry and other material parameters conform to those used in the R-20 program. Fig.5 and Fig.6 illustrate the stress contours resulting from blasting in conglomerate and homogeneous rock, respectively.

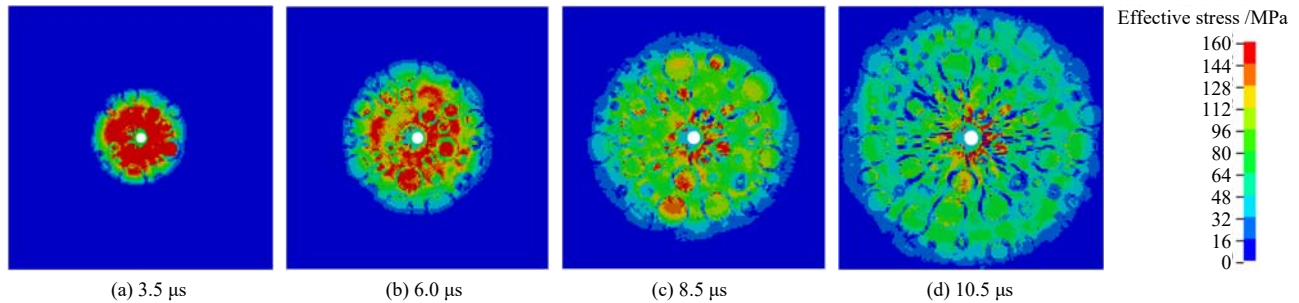


Fig. 5 Explosion stress in conglomerate

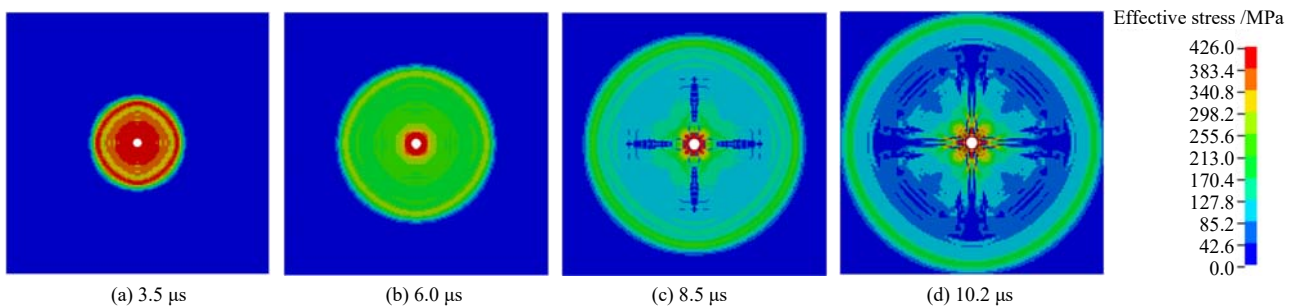


Fig. 6 Explosion stress in homogeneous rock mass

As shown in Fig.5, following the detonation of the explosive charge, the blast-induced stress waves propagated outward in an approximately spherical waves pattern. The amplitude of these stress waves rapidly attenuated with increasing distance from the source. It was particularly noteworthy that the propagation of blast stress waves in conglomerate rock, which composed of gravel, matrix, and cemented interfaces, did not exhibit uniform stress rings. This phenomenon can be attributed to heterogeneous nature of these components, which cause multiple reflections and scattering of stress waves across different media.

Significant stress concentrations were also observed within the conglomerate, attributable to the relatively higher density and elastic modulus of the gravel and cemented interfaces, resulting in greater stress intensities at equivalent distances from the blast hole compared to the matrix. A comparison between Fig.5 and Fig.6 revealed that at any given time step, both the intensity and spatial extent of stress waves in the conglomerate were lower than those in the homogeneous rock. This indicated a slower propagation velocity of stress waves within the conglomerate, primarily due to its complex internal structure, lower overall density, and reduced longitudinal wave velocity. Additionally, the presence of the low-density matrix further impeded stress wave transmission.

Figure 7 depicts the time history of effective stress in gravel, cementation interfaces, and matrix at distances of 5 mm, 20 mm, and 35 mm from the blast hole. As shown in Fig.7 (a), at 5 mm, the peak effective stress in the gravel reached 613.3 MPa, while the cementation interfaces and matrix exhibited peak effective stresses of 224.1 MPa and 273.6 MPa, respectively. The gravel sustained the highest effective stress, followed by the matrix, with the cementation interfaces experiencing the lowest stress levels. Although gravel possessed higher strength and toughness, the particles near the blast hole experienced more intense stress waves effects, resulting in compressive damage within all three media in the vicinity of the blast hole. Fig.7(b) and Fig.7(c) illustrate that the peak effective stresses at distances of 20 mm and 35 mm for gravel, matrix and cementation interfaces decreased to 140 MPa, 82.3 MPa, 71.2 MPa and 48.3 MPa, 32.8 MPa, 27.5 MPa, respectively. The effective stress values in the different media diminished with increasing distance from the blast source. Due to the inherent yield stresses of the materials, the effective stresses in the cemented interfaces and matrix first reached their respective yield thresholds, triggering the accumulation of plastic damage strain. Consequently, cracks preferentially initiated and propagated within the cemented interfaces and matrix.

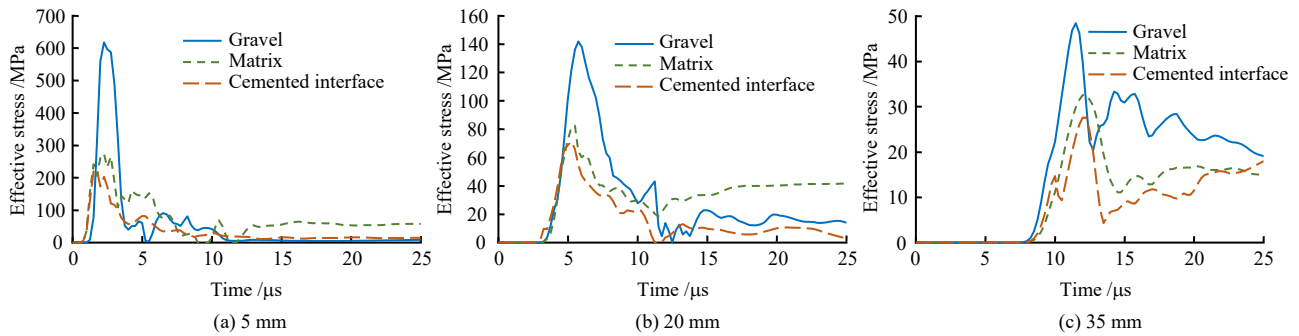


Fig. 7 Effective stress–time curves of gravel, cemented interface, and matrix at different distances from the blast hole

Figure 8 depicts the variation of peak equivalent stress in gravel, cementation interfaces, and matrix with increasing distance. The peak stress in gravel attenuated most rapidly (attenuation coefficient of 1.14), followed by the matrix (0.95), and finally the cementation interfaces (0.92). This trend aligns with the evolution pattern of the blasting stress contour in conglomerate illustrated in Fig.5.

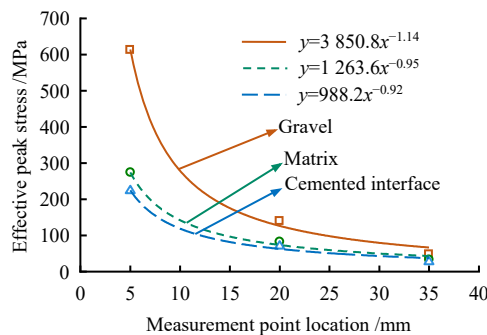


Fig. 8 Patterns of peak equivalent stress with distance for gravels, cementing surfaces, and matrices

3.3.2 Damage evolution law

Figures 9 and 10 depict the evolution of blast-induced damage in conglomerate and homogeneous rock masses, respectively. As shown in Fig.9, the energy generated by the blast rapidly transmitted to the inner wall of the blast hole, resulting in a localized expansion phenomenon and the formation of a crushed zone around the blast hole. With increasing radial distance, the conglomerate did not undergo compressive

damage; instead, only tensile damage was observed. As the damage continued to propagate outward, a distinct phenomenon emerged wherein the damage path circumvents the gravel, indicating a shift in the crack propagation pattern. At this stage, damage was primarily concentrated within the matrix and along the cementation interfaces. By 14.7 μ s, the damage evolution has essentially reached completion, and the medium-to-far-field regions remained largely intact. Notably, the gravel sustained only minor damage, while typical tensile failure occurred along the cementation interfaces due to reflected tensile waves in their vicinity. Observations of Fig.9(d) indicate that the damage zoning and damage modes of the conglomerate are consistent with the aforementioned theoretical analysis, namely the crushed zone where gravel clasts undergo comminution, the effective fracture zone where gravel clasts develop fractures, and the fracture zone where only the matrix suffers tensile failure.

A comparison between Fig.9 and Fig.10 reveals significant differences in the damage evolution patterns of conglomerate and homogeneous rock masses under blasting. In the homogeneous rock mass, the crushed and fractured zones developed in a relatively symmetric manner around the blast hole. In contrast, the crushed and fractured zones in the conglomerate were highly heterogeneous. A comparison of the two damage evolution processes further indicated that damage within the matrix of the conglomerate attenuated more slowly than in the homogeneous rock, whereas damage in the gravel attenuated more rapidly. This

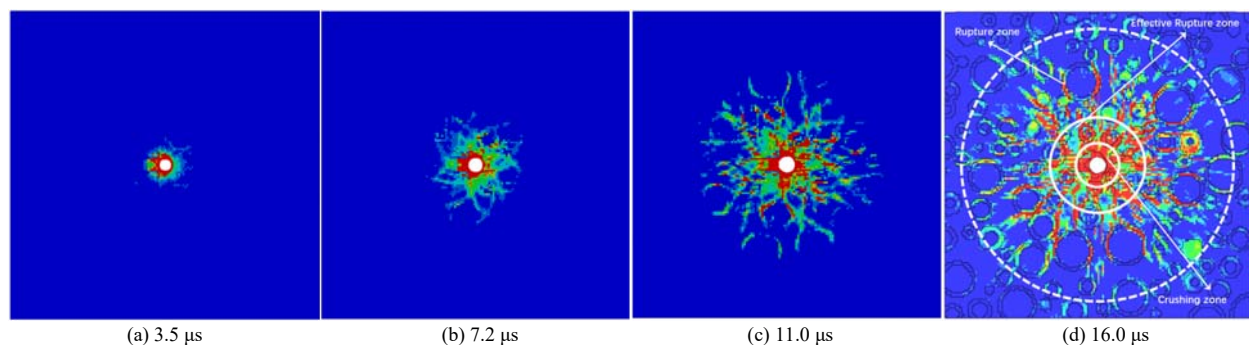


Fig.9 Blast damage cloud maps of conglomerate

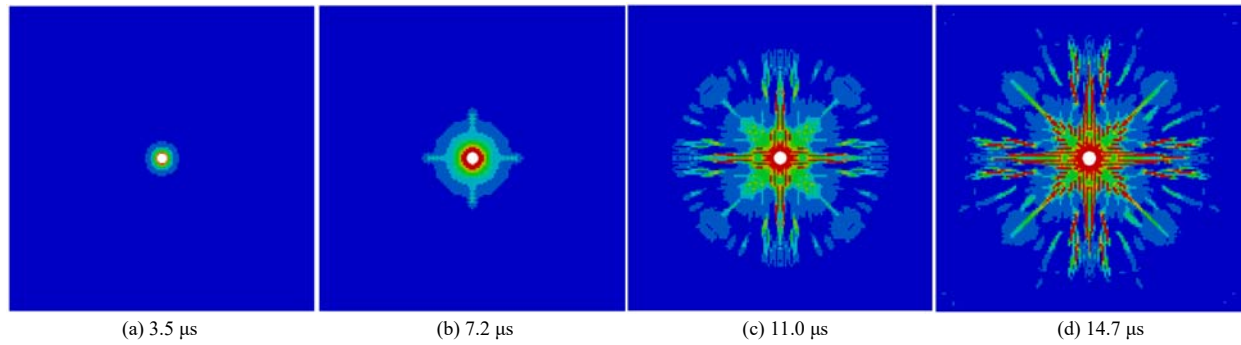


Fig. 10 Blast damage cloud maps of a homogeneous rock mass

behavior can be attributed to two primary factors: first, the blast energy preferentially propagates into the matrix due to its relatively weaker mechanical properties; second, stress waves undergo transmission and reflection at the cementation interfaces, leading to additional energy dissipation at these locations.

The observations from Fig.9(d) confirm that the final damage zoning and failure modes within the conglomerate align with the theoretical analysis above, encompassing the crushed zone, the effective fracture zone, the fracture zone, and the elastic zone. To unify the calculation parameters in the theoretical calculation and numerical simulation, the main parameters in the theoretical calculation were extracted from the numerical simulation results: the peak initial pressure at the blast hole wall P_0 was determined by extracting the first peak value of the pressure history curve of the elements adjacent to the detonation center; the geometric attenuation exponent n and material damping coefficient β were obtained via least-squares fitting based on the data of radial stress variation with distance; the tangential stress amplification factor k_t was calculated as the ratio of the peak tangential stress to the peak radial stress at the same position; the interfacial wave amplification factor γ was determined by comparing the peak stresses in the interface region and the matrix region; the peak tangential stress at the interface T was extracted from the maximum shear stress near the interface; and the interfacial stress attenuation exponent p was obtained by fitting the power-law attenuation law of the interfacial stress intensity factor along the radial direction. The results of the theoretical calculation and numerical simulation are shown in Fig.11. The numerical simulation results are in good agreement with the theoretical calculation results, with an error within 10%.

3.4 influence of explosive type and blast hole diameter on the blasting effect of conglomerate

Figure 12 illustrates damage contour maps for three types of explosives—TNT, Type-2 emulsion explosive, and low-density explosive—at blast hole diameters of 1.5 mm, 2.0 mm, and 2.5 mm. A horizontal

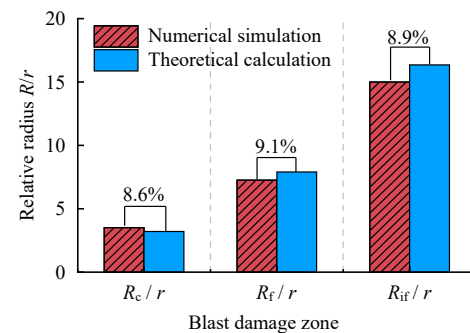


Fig. 11 Comparison between numerical simulation and theoretical results

comparison of Fig.12 indicates that, under blasting with different explosive types, the conglomerate exhibits similar damage patterns: the extent of the crushed and fractured zones, as well as the number of cracks, increases with increasing blast hole diameter. From the vertical comparison, it is evident that, at the same blast hole diameter, TNT produced the largest crushed zone, followed by the Type-2 emulsion explosive, with the low-density explosive producing the smallest. However, as blast hole diameter increased, the fractured zone associated with the low-density explosive gradually exceeded those produced by TNT and the emulsion explosive. Based on the principle that a smaller crushed zone combined with a larger fractured zone indicated better blasting performance, it can be concluded that the configuration shown in Fig.12(g) yields the optimal blasting effect. Therefore, for blasting operations in conglomerate rock, the use of large-diameter blast holes in conjunction with low-density explosives is more desirable.

To further investigate the influence of explosive type and blast hole diameter on the blasting performance in conglomerate rock, this study introduced the damage fractal dimension and an irregular shape area identification method. These approaches enabled a quantitative characterization of the damage features in the conglomerate induced by blasting.

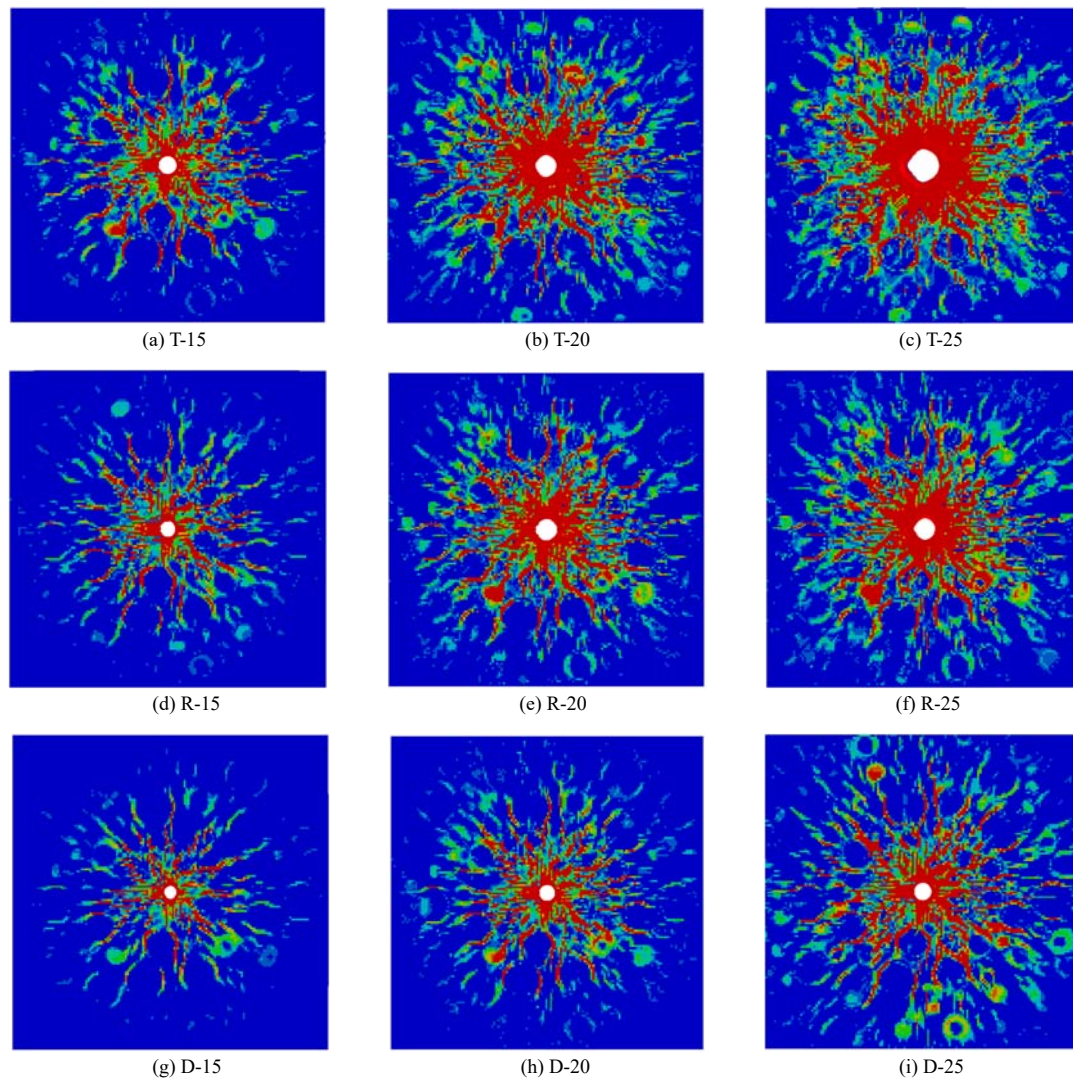


Fig. 12 Blast damage cloud maps of conglomerate under varying blast hole diameters for three types of explosives

3.5 Influence of explosive type and blast hole diameter on the crushed zone

3.5.1 Area statistical method for blast crushed zones

As shown in Fig.12, the crushed zone generated in conglomerate rock under blasting exhibits an irregular geometry. Therefore, this study employed the ImageJ software to identify and calculate the area of the crushed zone following blasting, as illustrated in Fig.13. According to the findings reported in reference^[44], a damage threshold of 0.8 effectively captures the onset of critical fracture, with simulation results showing good agreement with experimental observations. Based on this, the present study adopted a critical damage threshold of 0.8. The blasting-induced damage in the rock mass were visualized using the post-processing software LS-PrePost, where regions with a damage value equal to or greater than 0.8 were marked in white, and the remaining areas were rendered in gray.

Firstly, the damage contour images from the numerical simulation were converted into 8-bit grayscale images. Subsequently, a threshold segmentation

procedure was executed: grayscale values exceeding the threshold were transformed into black pixels, whereas those falling below the threshold were converted into white pixels. This process produced a binary image containing only pixel values of 0 and 255, where the white regions correspond to the crushed and fractured zones, and the black regions represent intact rock. Thereafter, the “wand (tracing)” tool in ImageJ was used to determine the number of pixels within the crushed area. Based on the known ratio between image area and total pixel count, the actual area of the crushed zone in the conglomerate was quantitatively determined.

3.5.2 Results and discussion

As illustrated in Fig. 14, for these three types of explosives, the area of the crushed zone generated by blasting expands with an increase in blast hole diameter. Damage within the crushed zone is predominantly attributed to compressive failure induced by the shock wave. From this, it can be inferred that the effective action range of the shock wave widens as the blast hole diameter increases. The

growth coefficients for the crushed zone area are 4.00, 3.14, and 1.82 for TNT, No. 2 rock emulsion explosive, and low-density explosive, respectively. These figures

demonstrate that as the explosive charge escalates, the crushed zone area exhibits the slowest growth for low-density explosives and the fastest growth for TNT.

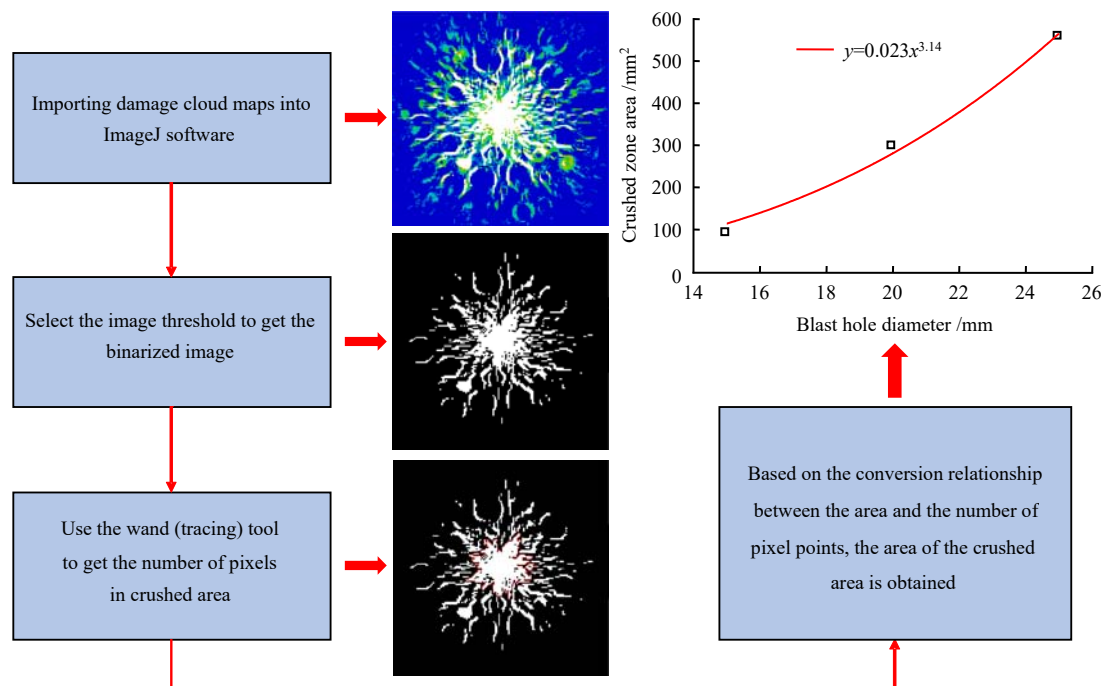


Fig. 13 Sketch of blast crushed zone area calculation

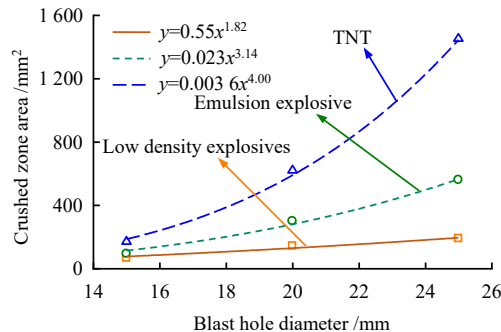


Fig. 14 Influences of explosive type and blast hole diameter on the area of crushed zone in conglomerate

The extent of the crushed zone is subject to the influence of the explosive type employed. When dealing with smaller blast hole diameters, the impact of explosive type on the crushed zone's area is comparatively negligible. Nevertheless, as the blast hole diameter expands, this influence grows increasingly pronounced. This phenomenon arises because the energy density of each explosive type remains consistent; however, with an augmentation in charge diameter, the disparity in total energy among various explosives becomes more conspicuous.

3.6 Influence of explosive type and blast hole diameter on the fractured zone

3.6.1 Statistical method for fractal dimension of blast-induced fractures

Previous studies have indicated that the distribution

characteristics of blast-induced fractures under blast loading follow fractal principles. The fractal dimension serves as a quantitative measure of the fracture distribution, with larger fractal dimensions corresponding to a higher degree of rock fragmentation^[45]. Considering the exceptionally complex fracture patterns in conglomerate subjected to blast loading, which are difficult to quantify, this study employs fractal theory to quantitatively analyze the effects of three explosive types and varying blast hole diameters on the distribution characteristics of explosive fractures.

At present, the calculation methods of fractal dimension mainly include Hausdorff dimension, self-similarity dimension, capacity dimension and counting box dimension. Among them, the box counting dimension has been widely used in fractal research because it can intuitively reflect the degree of occupation of the target in the study area, and the calculation method is relatively intuitive and simple. The process of calculating the fractal dimension of blast damage using the box counting method is shown in Fig.15. In this method, the numerically simulated blast damage image is covered by a box with a side length of δ ; the number of boxes containing crack pixels, denoted as $N(\delta)$, is then counted; the side length of the box δ is progressively reduced, and as it approaches 0, the fractal dimension D_f of the blast damage can be determined^[46].

$$D_f = -\lim_{\delta \rightarrow 0} \frac{\lg N(\delta)}{\lg \delta} \quad (18)$$

Since it is difficult to make the box dimension δ converge to 0 in practical calculations, usually after finding out the $\lg \delta$ and $\lg N(\delta)$ data of multiple groups, the fitted linear equation (19) is obtained by

linearly fitting the data points $(\lg \delta, \lg N(\delta))$ by the least squares method, and the slope of the linear equation is the fractal dimension.

$$\lg N(\delta) = -D_f \lg \delta + b \quad (19)$$

where b is the intercept of the fitted linear equation.

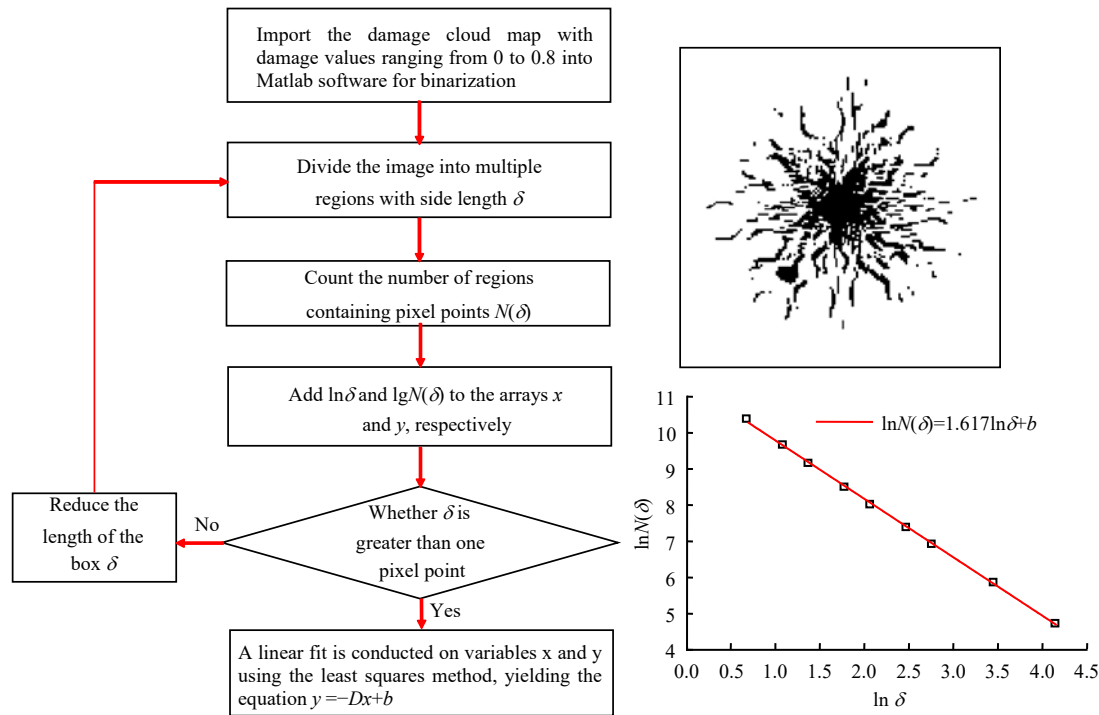


Fig. 15 Flowchart for calculating the fractal dimension of blast-induced cracks

3.6.2 Results and discussion

As illustrated in Fig.16, the fracture extent resulting from blasting with three distinct types of explosives expands as the blast hole diameter increases. The damage within the fractured zone is primarily attributed to tensile failure of the rock mass caused by stress waves. Therefore, it can be concluded that the effective action range of stress waves enlarges as the blast hole size increases. The growth coefficients of the fractured zone for low-density explosive, Type-2 emulsion explosive, and TNT are 0.387, 0.313, and 0.299, respectively, indicating that increasing the explosive consumption more significantly promotes fracture zone development when using low-density explosives. This is because the low-density explosive has a lower wave impedance, which is more matched with the wave impedance of conglomerate. Thus, more explosive energy can be efficiently coupled into the rock mass during blasting. When its stress wave propagates inside the conglomerate, it can overcome greater geometric diffusion and internal friction losses, so the amplitude of the stress wave attenuates more slowly as the distance increases.

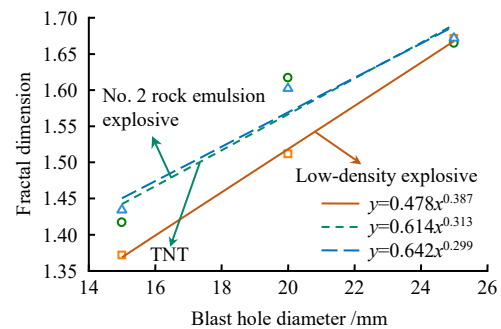


Fig. 16 Influences of explosive type and blast hole diameter on fractal dimension of blast-induced cracks in conglomerates

4 Conclusions

(1) Based on multi-media wave dynamics, a theoretical calculation model of conglomerate blasting zoning is proposed for the structural characteristics of conglomerate. The blast-affected domain is subdivided into four distinct regions: the crushed zone, the effective fractured zone, the fractured zone, and the elastic zone. And the theoretical calculation and numerical simulation results were compared to verify the accuracy of the theoretical model.

(2) Under blast loading, gravel is subjected to

higher effective stress. As the explosive stress wave propagates through the conglomerate, complex transmission and reflection phenomena occur. A pronounced stress drop exists at the cementation interfaces, and the stress differential between gravel and matrix decreases with increasing distance from the blast source. As a result, the damage to gravel diminishes rapidly with distance, whereas the damage to the matrix attenuates more gradually.

(3) The type of explosive and blast hole diameter have a significant influence on the blasting effectiveness in conglomerate. With increasing blast hole diameter, low-density explosives exhibit the slowest growth in the area of the crushed zone compared to high-energy explosives such as TNT, whereas the fractal dimension of blast-induced fracture damage demonstrates the fastest increase.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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