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The Effect of Initiation Time Delay and Sequencing on Rock Damage in Multi-Hole Blasting

Magreth Sungwa Dotto * and Yashar Pourrahimian

Department of Civil & Environmental Engineering, University of Alberta, Edmonton, AB T6G 2R3, Canada; yashar.pourrahimian@ualberta.ca
* Correspondence: magreth@ualberta.ca

Abstract: Rock fracturing by blasting is the most common and efficient method of rock fragmentation in mining operations. The fragmentation size affects the productivity and costs of downstream operations and is influenced by the rock mass and blast design encountered. The encountered rock mass is the unmodifiable parameter in blasting. Therefore, blasting improvements can be achieved through blast design, which includes explosive selection, geometrical design, and initiation sequencing and delays. Stress wave interactions between blastholes can improve or diminish fracturing. The analysis conducted in this study through numerical modelling indicates an improvement in blast outcomes with appropriate delay and sequencing in some cases. The optimum delay ensures the formation of fractures on the succeeding blasthole and constructive interactions with the stress wave from the preceding blasthole, increasing the stress pulse and fracturing. While it is insignificant in intact rock blasting, the firing sequence is vital when blasting through the contacts of soft and hard rocks or joints, depending on the infill material. Sequential initiation and the firing direction do not improve fracturing in all cases; for example, when blasting through an empty joint, the joint acts as a free face with minimum to no interaction of the stress wave from adjacent charges. In such cases, simultaneous initiation can be used with caution based on the intensity of induced vibrations.

Keywords: blast fragmentation; numerical simulation; initiation sequencing; initiation delays; rock mass properties

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1. Introduction

Drilling and blasting are common operations in rock fragmentation to facilitate rock excavation in mining and civil works. The fragmentation process occurs quickly and involves several mechanisms, making it challenging to study. From a single blasthole, the fracture mechanism involves a combined action of shock waves and explosion gases where shock waves act first, causing the initial fracturing, followed by the explosion gases wedging into the cracks and extending fractures.

Three main damage zones form around the blasthole: the crushed, fracture/fragmentation, and seismic zones. The crushed and fracture zones are the major focus when blasting for rock excavation. The crushed zone is formed from the higher compressive stresses from the detonation wave and the rapid expansion of detonation gases, producing higher shock waves that act on the inner side of the blasthole and the surrounding rock. After it travels through a certain distance, the shock wave attenuates and falls below the dynamic compressive strength of the rock. As the rock yields, it releases the tangential stress, causing longer and more spaced radial cracks in the fractured zone. These cracks propagate as

long as the tensile component of the compressive stress is higher than the dynamic tensile strength of the rock [1]. When the wave encounters a free surface, it is reflected, and if it is strong enough, it causes further fracturing (spalling). As the wave travels outwards, it attenuates further and becomes an elastic wave that can deform but not fracture rock within the seismic zone. The size of these zones varies vastly depending on the explosive strength and encountered rock mass. The explosive gases expand into the cracks, extending fractures and forming the fragmentation.

In mining production, regardless of whether on the surface or underground, several holes are initiated in the blast shots. Both the total number of blastholes and their arrangement, as well as the design of the initiation pattern and decision between simultaneous or sequential initiation, are critical in rock fragmentation and affect the safety and stability of the remaining rock and structures. In multi-hole blasting, spacing between the holes and time delay is important in enhancing fragmentation by allowing enough time for the cracks to grow between the holes with minimum interference. Other than improving fragmentation, initiation sequencing and delays play a major role in the blast-induced vibration, significantly impacting the stability of the pit wall and nearby structures. Müller et al. [2] suggested that vibration control can be achieved by adjusting the explosive type, charge weight, and the borehole length and diameter. Their study, based on momentum theory, suggests that consecutive short delays with smaller charges may generate higher ground vibrations compared to simultaneous ignition. This implies that while short delays can enhance fragmentation, special attention should be given to blast-induced vibrations. The 8 ms rule [3,4] proposed by the USBM for separate charges is widely used for ground vibration control. Several researchers have debated this theory due to the complex nature of blast-induced vibrations in rock masses, where factors such as wave superimposition and rock properties influence the vibration behaviour beyond a fixed delay threshold.

Katsabanis et al. [5] concluded that simultaneous initiation results in coarser fragmentation using a series of small-scale tests. Studies conducted by Rossmanith [6] and Vanbrabant and Espinosa [7] indicated that shorter delays are favourable in improving fragmentation because the stress wave interaction between the holes enhances the tensile tail of the stress wave. On the contrary, the theoretical and numerical investigation conducted by Yi et al. [8] and Yi, et al. [9] indicated that it is impossible to improve fragmentation from wave superimposition when the stress waves interact between the blastholes because the increase in tensile stress occurs in a very small area around the collision zone. Johansson and Ouchterlony [10] conducted a series of small-scale tests and observed only minor fragmentation improvements due to the interaction of shock waves.

Stagg and Rholl [11] observed that the optimum fragmentation is achieved when the second hole is initiated after the failure process in the first hole is completed. Saadatmand Hashemi and Katsabanis [12] suggested that the optimum delay is the delay that allows enough time for cracks to grow and precondition the surrounding rock for neighbouring blastholes, and it is a function of the rise and duration of the stress wave pulse, the stress wave speed, and crack propagation in the rock mass. These studies provide important insights into the interaction between stress waves produced by the adjacent blastholes, but the influence of the heterogeneous rock mass on the blast process and how it affects this interaction is still unclear.

Extensive studies conducted on the factors influencing fragmentation by blasting indicate that the intact rock's physical, mechanical, and structural properties highly influence the blast outcomes [13–17]. The study conducted by Dotto and Pourrahimian [18] concluded that the presence of rock structures influences the propagation of stress waves and fractures and especially depends on the properties of infill materials and the width, continuity, intensity, and orientation of such structures. Since the rock mass properties

cannot be changed, the choice of explosives, geometric design parameters, and initiation sequencing can be tailored to mitigate the influence of rock mass properties and achieve the desired outcomes. A similar study by Müller [19] suggests that the acoustic impedance of the rock and the properties of structures are useful parameters in deciding the explosive properties and design parameters to ensure good fragmentation and reduce adverse effects such as ground vibrations and fly rock.

Due to the complex nature of the rock mass and its interaction with explosive energy, numerical modelling has been used extensively for several decades to study the blast wave behaviour and provide insights into the blasting process [17,20]. The ability to track the growth and nucleation of cracks of brittle materials from the damage evolution laws has made finite element modelling (FEM) more desirable in blasting simulation [21]. The Riedel–Hiermaier–Thoma (RHT) constitutive material model with homogenized micromechanical descriptions and interdependences between stress, strain, plastic strain, strain rate, damage, and failure implemented in LS-DYNA was successfully used to model the dynamic behaviour of concrete [22]. This model is widely used to study rock fragmentation by blasting [21,23–25].

This study implements the RHT model in LS-DYNA to study the interaction of explosive energy between two blastholes. The study is divided into two sections. In the first section, the effect of initiation delay on the burden-induced damage of the intact rock is investigated. The second part examines how variations in rock mass properties influence the initiation delay and firing sequence in achieving better fracturing. Overall observations are used to suggest techniques to improve blast-induced fragmentation in variable rock masses through firing sequence and initiation delays. The model uses data from an existing mine, and the simulation model is verified and validated using the field blast results.

2. Numerical Modelling Verification and Validation

LS-DYNA, a nonlinear transient dynamic finite element code, is used to simulate rock blasting [26]. LS-DYNA can successfully model the interaction between the solid material (rock) and fluid and gas flow (explosion gases) using the Lagrangian algorithm and Arbitrary Lagrangian–Eulerian (ALE), respectively; incorporate coupling between the Lagrangian and ALE interface; and apply boundary conditions to restrict elements' movements as needed. Two-dimensional (2D) and three-dimensional (3D) models are used in this study. The 3D model is used in the initial modelling to illustrate the stress distribution and overall damage in a full-size bench, and later on in the analysis, the 2D model is used to study the fragmentation process and the interaction between blastholes, preferably due to the computational simplicity.

2.1. The RHT Material Model

The numerical model consists of the rock medium and explosives. The RHT model developed by Riedel et al. [27] and implemented by Borrvall and Riedel [22] in LS-DYNA is calibrated to capture the effect of the strain rate on strength and used to model the rock medium and track damage development under blast loading. The material model contains three limit surfaces that define the strength of the material: the initial elastic yield surface, residual friction surface, and failure surface, as illustrated in Figure 1. The surfaces represent the reduction in material strength in different meridians and the effect of the strain rate. The first surface is the yield surface, below which the model is elastic. Beyond the yield surface, the material deforms plastically with linear hardening descriptions. When stress reaches the failure surface, the damage strain accumulated governs damage evolution. The damage variable of the RHT model (D) is defined using Equation (1), where ε_m^P is the accumulated plastic strain and ε_f^P is the plastic strain failure. D varies from 0 to 1, where

0 represents the undisturbed material and 1 is a fully damaged material. More information about the RHT model can be found in Borrvall and Riedel [22].

$$D = \sum \frac{\Delta \varepsilon_m^P}{\varepsilon_f^P} \quad (1)$$

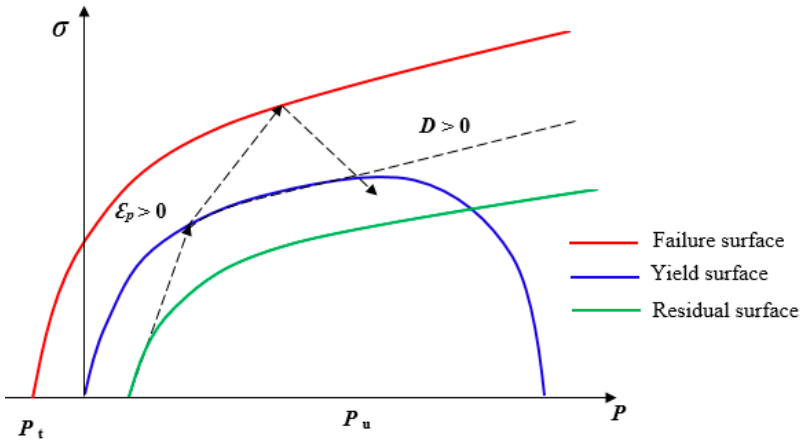


Figure 1. Stress limit surfaces and the loading scenario [22].

The RHT model parameters were determined for the banded iron formation (BIF) rock studied by Dotto et al. [13] from Nyankanga Pit's Geita Gold Mine in Tanzania. The mechanical properties of the rock are presented in Table 1. The calibrated RHT model parameters can be found in Dotto and Pourrahimian [18].

Table 1. Mechanical properties of the BIF rock.

Rock Property (Units)	Density (g/cm^3)	UCS (MPa)	Tensile Strength (MPa)	Young Modulus (GPa)	Poisson Ratio
Value	2680	126.02	14	90.8	0.24

2.2. Explosive Properties and Parameters

The explosive detonation was modelled using the high explosive burn material and Jones–Wilkins–Lee (JWL) EOS. The JWL equation of state is a high-energy combustion model that can reliably predict higher explosion pressures. The model calculates the pressure detonation product P_{cj} from the expression in Equation (2) [28].

A, B, R_1, R_2, and ω are material constants; E is the detonation energy per unit volume, and V_1 is the relative specific volume of detonation products. The explosive used for blasting in Nyankanga Pit is a manufactured emulsion by ORICA (Fortis Extra) [29], and its properties are summarized in Table 2. The explosive parameters were obtained from site measurements performed by Dotto et al. [13], and the material constants were adapted from a similar emulsion explosive E682 calibrated by Hansson [30]. The JWL parameters used are presented in Table 3.

$$P_{cj} = A\left(1 - \frac{\omega}{R_1 V_1}\right)e^{-R_1 v_1} + B\left(1 - \frac{\omega}{R_2 V_1}\right)e^{-R_2 V_1} + \frac{\omega E}{V_1} \quad (2)$$

Table 2. Explosive properties.

Explosive Property (Units)	Density (g/cm^3)	Minimum Diameter (mm)	VOD (km/s)	Bulk Energy (MJ/kg)
Value	1.10–1.25	64	4.1–6.7	3.47–4.35

Table 3. Parameters of the JWL equation.

Explosive Type	Density (kg/m^3)	*VOD* (m/s)	P_{cj} (GPa)	*A* (GPa)	*B* (GPa)	R_1	R_2	ω	E_o (kJ/cm^3)	v_o
E682	1207	4789	6.926	276.2	8.44	5.2	2.1	0.5	3.87	0

2.3. Simulation Model Preparation, Verification, and Validation

Using the RHT material model, a rectangular rock specimen with a height of 13.5 m, representing a bench height of 10 m, a sub-drill of 1.5 m, and a pit floor of 2 m, was generated. The bench design parameters are a blasthole diameter of 203 mm, a burden of 5.5 m, a spacing of 6.5 m, a charge column height of 7 m, and a stemming height of 4.5 m, as illustrated in Figure 2. The RHT material was modelled using Lagrangian element formulation, and the explosive was modelled using the ALE media. The coupling mechanism was introduced using Lagrange in solid formulation, with Eulerian elements as the master and Lagrangian elements as the slave. Simulations were conducted for mesh size sensitivity analysis using various mesh sizes (ranging from 2 cm to 5 cm, to 3 cm, and to 10 cm), and it was determined that a 2.5 cm mesh size was optimal near the charge. This mesh size was then gradually increased to a maximum of 8 cm beyond half a metre from the blasthole. Non-reflecting boundaries are selected for the four sides, and two sides are left as free faces with reflecting boundaries. Blasthole initiation takes place 1.5 m from the bottom of the blasthole at 0.0 ms, and the model runs for 3 ms. The damage contours for Section A and Section B at 3 ms, which are shown in Figure 2, are presented in Figure 3a,b, respectively. The crushed zone is initially 0.184 mm at 0.56 ms and later extends to 0.31 mm at 3 ms. The pressure and PPV at the blasthole wall are 2640 MPa and 202 m/s, respectively.

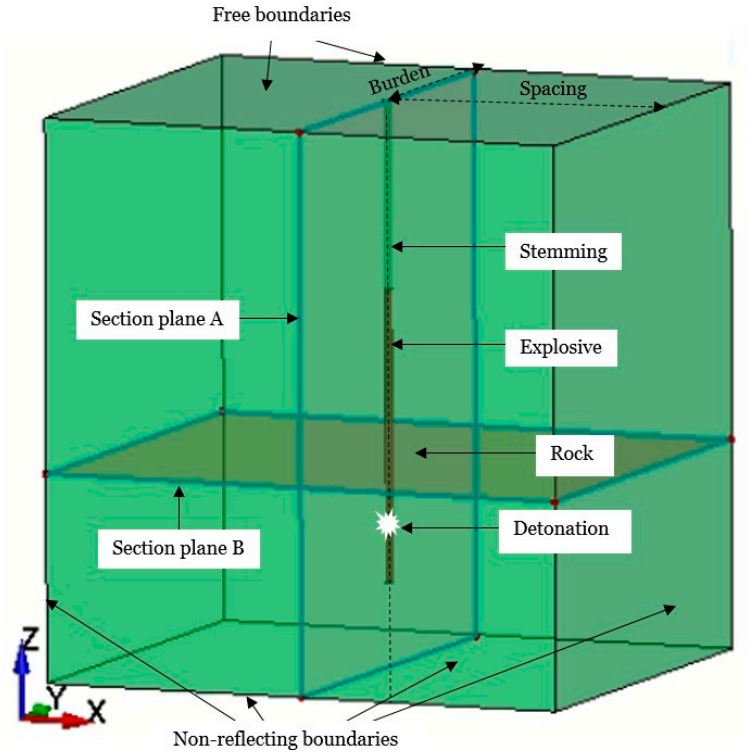


Figure 2. Full-scale simulation model.

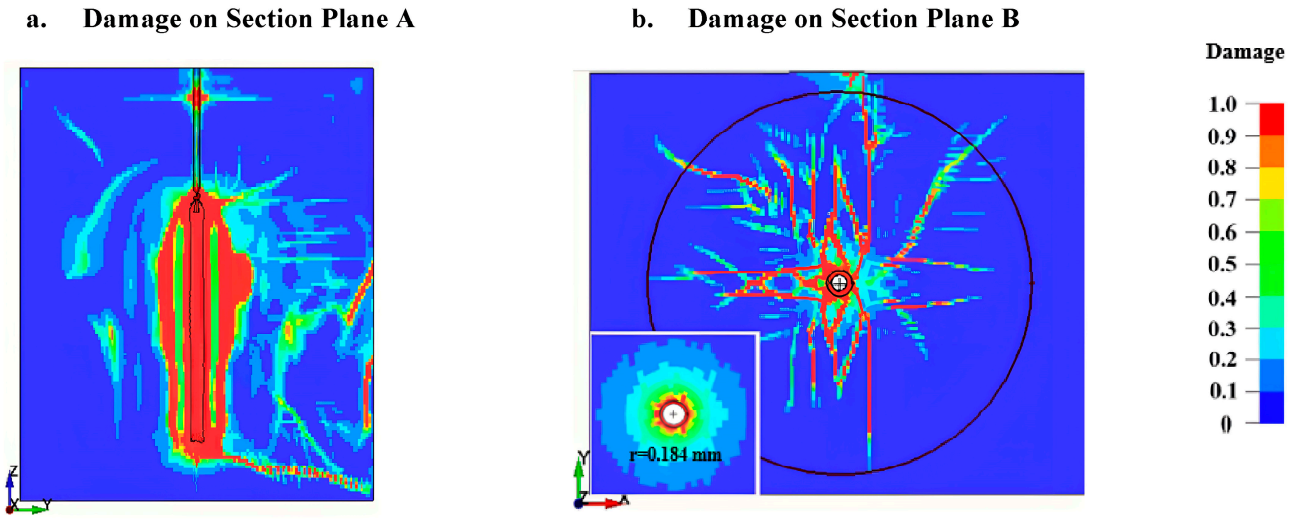


Figure 3. Damage distribution in a bench.

Rapid attenuation occurs when the blasthole wall and the surrounding rock are pulverized, making the pressure and PPV at the end of the crushed zone 1230 MPa and 94.3 m/s, respectively. Gentle attenuation occurs in the fractured zone due to spreading, and the wave energy usage in stress wave and fracture propagation. The pressure and PPV at the boundaries of the model, which are also at the limit of the fractured zone, are 18.7 MPa and 1.77 m/s, respectively.

The results obtained from the numerical simulation are similar to those of field measurements performed by Dotto et al. [13] and Dotto and Pourrahimian [18] on pressure and PPV attenuations as well as the extent of damage zones. The crushed zone extends to 0.17 m in the field measurements and 0.18 m in numerical simulations. The fracture zone extends to 5.25 m in field measurements and 5 m in simulations. The spalling effect caused by stress wave reflection at the free face is observed in both cases. Since the simulation model works as intended and provides similar results to the field measurements, the model is verified and validated.

2.4. Full-Scale and 2D Model Comparison

A 2D model is constructed along an x–y plane with the same dimensions as the full-scale model in the same plane. The stress wave pulse monitored at the blasthole wall is shown in Figure 4a for full-scale and 2D models. From the figure, the stress of the shock wave at the blasthole wall is around 2750 MPa and is observed to diminish at 1 ms with a faster rate in the full-scale model.

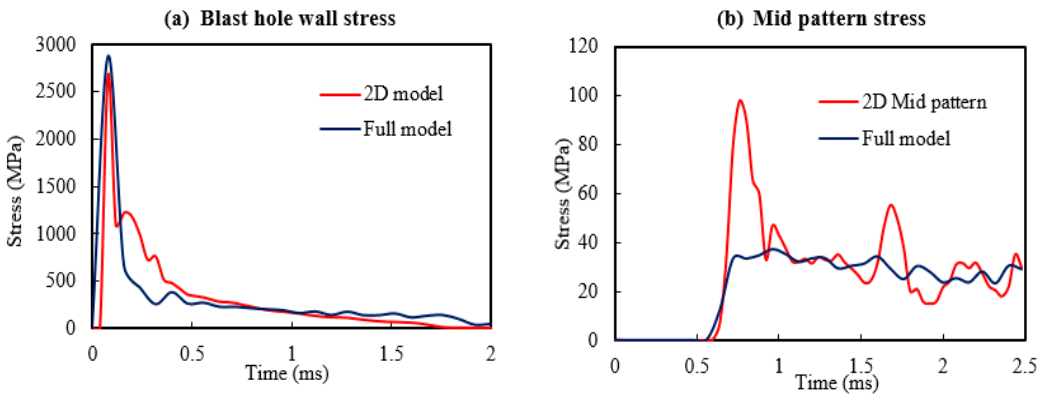


Figure 4. Stress distribution comparison between full bench and the 2D model.

The stress wave monitoring the mid bench at a burden of 2.75 m and a spacing of 3.25 m, as shown in Figure 4b, indicates that the wave arrives at 0.6 ms from the initiation in both models. A higher spike is observed on a 2D model, and the wave reflection at the free face causes a second spike. Higher stress in 2D can be attributed to artificial constraints introduced in the z-direction, which amplifies the stress concentration. The average stress is similar in both models. The comparison of damage intensity indicates more damage on a 2D model, while the fracture pattern and extent are more or less the same, as described in Figure 5.

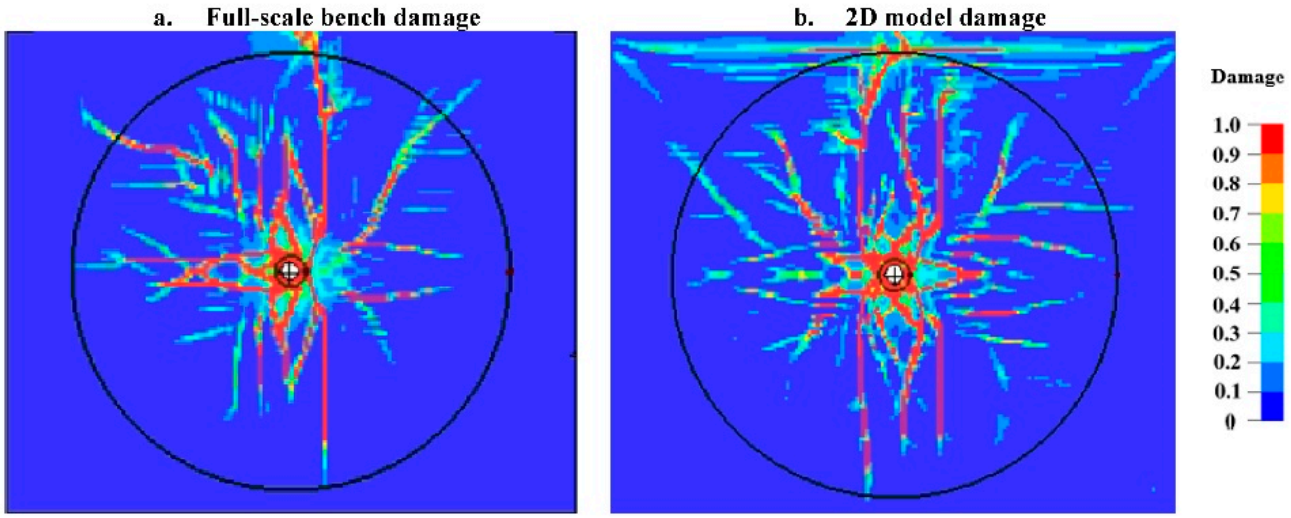


Figure 5. Damage intensity comparison between full bench and the 2D model.

3. Multi-Hole Blasting and Interactions Between Blastholes

The initiation delay and the spacing between the blastholes play an important role in blast fragmentation caused by the interaction between stress waves from the adjacent holes. Two blastholes with a 6.5 m spacing distance between them were modelled to analyze the effect of initiation delays on burden fragmentation. The initiation delay timing (time delay detonator) on the second blasthole varies from 0 to 1.5 ms for the same distance. Simulations were run by adjusting the delay in the second blasthole by 0.1 ms, and only significant changes in fracturing were reported. The initial analysis indicates that no further damage evolves after 2 ms from the detonation of the last blasthole. To ensure this time frame is achieved, all models are run for 4.2 ms. The stress wave interaction was analyzed for various rock mass properties, including the intact rock, soft and hard rock contact, and a joint between the blastholes.

3.1. Intact Rock

BIF rock properties are used in the RHT material model to simulate the intact rock, with emulsion as the explosive. A 2D axisymmetric model consisting of two blastholes is used for analysis. The results for the damage intensity as a function of delay timing are illustrated in Figure 6.

Fracturing is reduced significantly in the absence of a free face. When adjacent blastholes are fired simultaneously, the damage is concentrated directly across the blastholes axis where the stress wave is intensive. A wider area of the burden between the blastholes remains un-fractured. This is caused by the destructive interference of the stress wave, as illustrated by the elements' velocity vectors in Figure 7 and the stress curve plots at the mid-burden (spacing and burden = 3.25 m and 2.75 m) in Figure 8. When a 0.5 ms delay is applied on the second hole, the damage from the first hole increases with increased

delay; the interference moves closer to the second hole, causing less damage around it, as seen in Figure 6c.

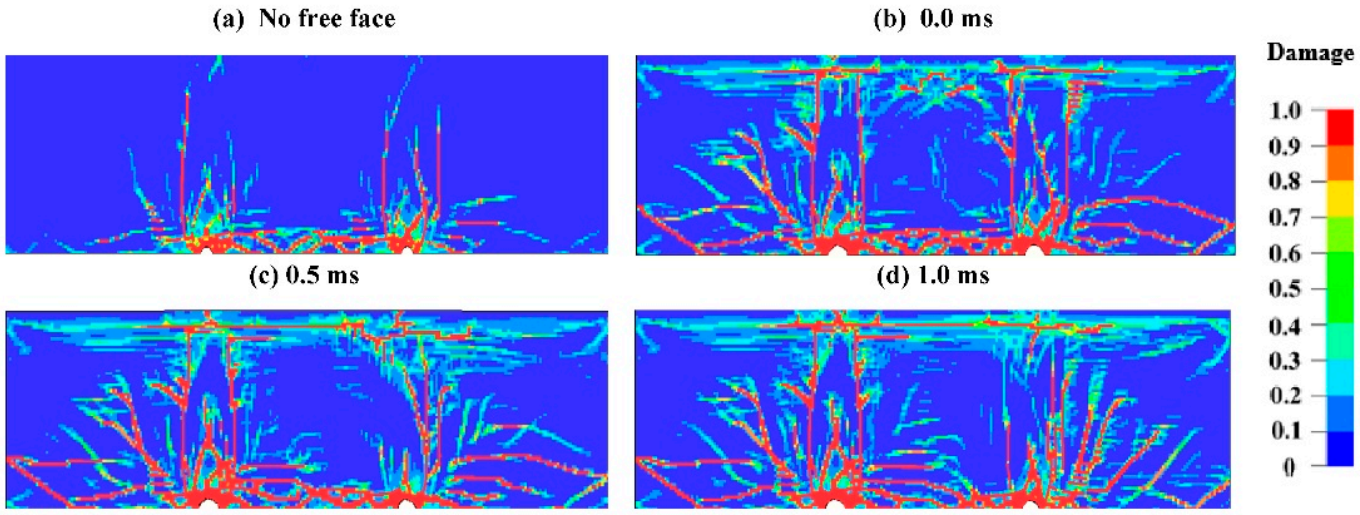


Figure 6. Damage intensity with delay in the intact rock.

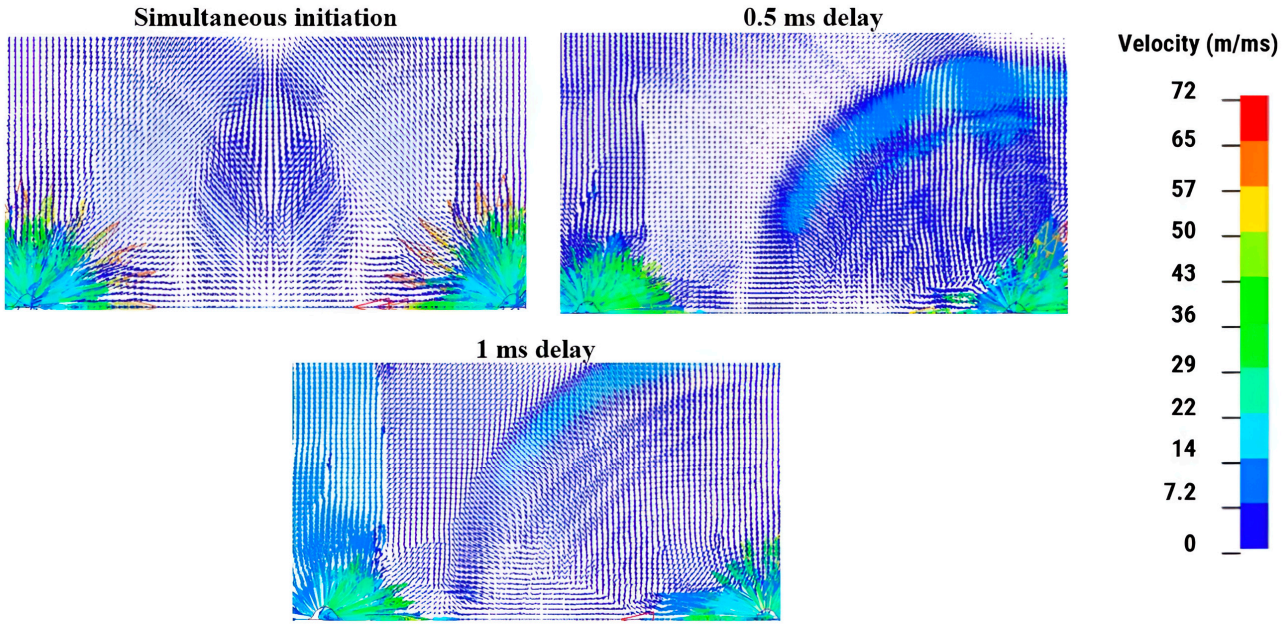


Figure 7. Velocity vector for various delays.

A further delay increase to 1 ms allows for the formation of fractures around the first hole with minimum influence on the second hole. The stress wave from the first hole attenuates quite significantly when the second hole detonates. As seen in Figure 8d, constructive interference occurs, increasing the wave pulse, fracturing between the blastholes, and eventually, increasing the overall damage, as seen in Figure 6d. A further increase in delay timing causes no further improvements.

As seen in Figure 8b, when blastholes are fired simultaneously, the second peak of the stress wave at the centre of the burden diminishes to almost zero once the waves meet, shortening the wave pulse. When the delay is 0.3 ms, i.e., near-instantaneous detonation, the second peak appears much quicker and is short-lived. At a 1 ms delay, the stress wave is in phase with one hole blast; it is therefore enhanced, and the wave pulse is extended.

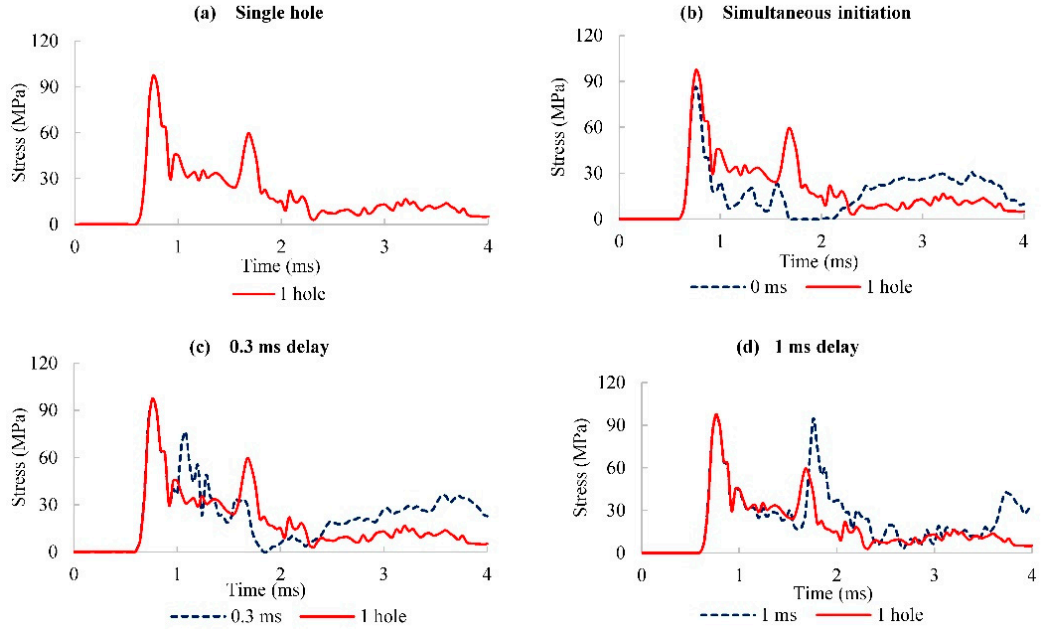


Figure 8. Stress curves mid-burden.

Shorter delays, in addition to causing destructive interference between the blastholes, also influence the stress concentration around the succeeding blasthole, as demonstrated in Figure 9. When the blastholes are initiated simultaneously, the stress around the first blasthole and the second blasthole is 1070 MPa and 1020 MPa, respectively; there is no influence on the second hole. The stress around the first hole remains the same throughout the delays. The stress on the second blasthole increases to 1420 MPa when the delay is 0.3 and 0.5 ms and falls back to 1020 MPa with a similar shape as the first hole at 1 ms.

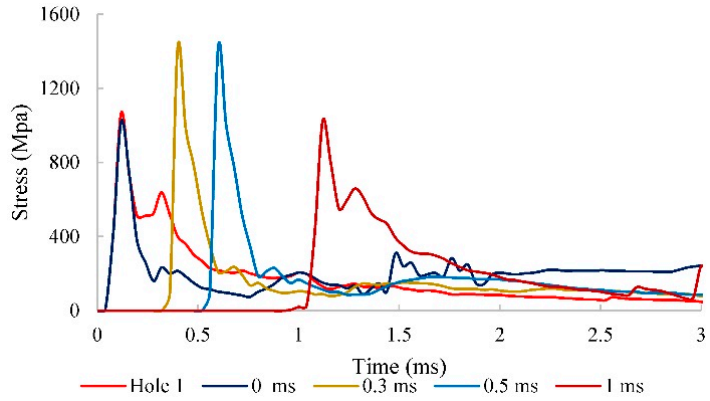


Figure 9. Stress around blastholes for various delays.

The optimum delay allows enough time for the fractures to form around the preceding hole and reduces the interference with the detonation of the succeeding holes and between the blastholes, hence improving fragmentation, as illustrated in Figure 10a. The optimum delay forms a smooth peak stress curve from the stress wave monitoring between holes at various distances, as seen in Figure 10b. The optimum delay for the intact rock used in the study is 1 ms, causing a 10% improvement in fracturing. Similar observations on the improvements of fragmentation with longer delays were reported by Tang et al. [31] from the experimental study on the influence of time delay on fragmentation in bench blasting. A further increase in delay timing did not yield any improvements in fracturing, as seen in Figure 10a.

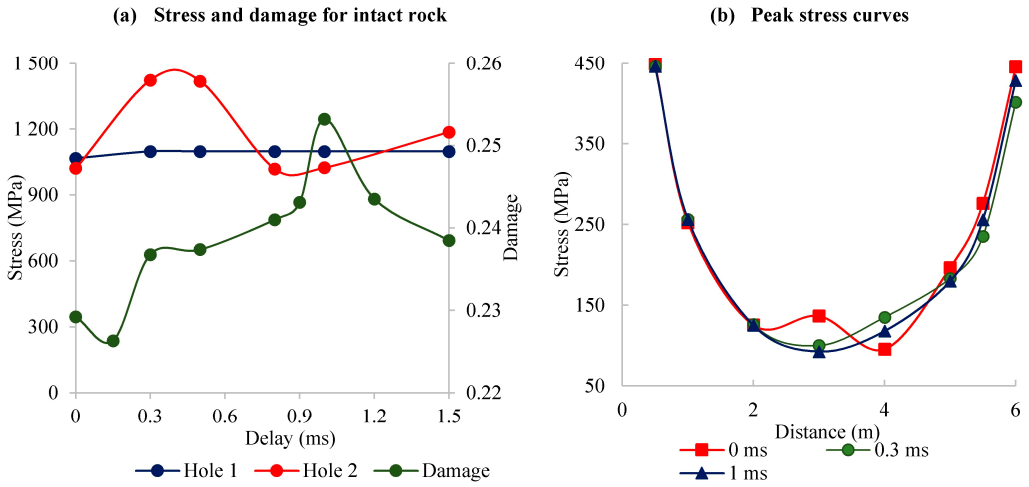


Figure 10. Stress and damage curves for intact rock.

3.2. Stress Wave Interaction Across Contacts

The rock mass is made of several features and structures. Rock contacts are geological features that form during the deposition or intrusion of magma, or faulting, which moves the rock and makes two different rocks with different properties come into contact. Rock contacts are common features in mining and can present challenges in rock mass fragmentation caused by blasting. To study the influence of rock contacts in stress wave interaction and fracturing from blasting, sandstone with RHT parameters calibrated from the experiment results by Jeong and Jeon [32] in Table 4 was introduced as a soft rock. The contact between hard rock and soft rock, i.e., between BIF and sandstone, is studied where the contact is introduced at 1.5 m from the first blasthole, as illustrated in Figure 11; the red dots are blastholes. More discussion can be found in Dotto and Pourrahimian [18].

Table 4. Sandstone physical and mechanical properties.

Density (kg/m^3)	UCS (MPa)	Tensile Strength (MPa)	Young Modulus (GPa)	Poisson Ratio	P-Wave Velocity (m/s)
2400	88	0.1 × UCS	25	0.3	2589

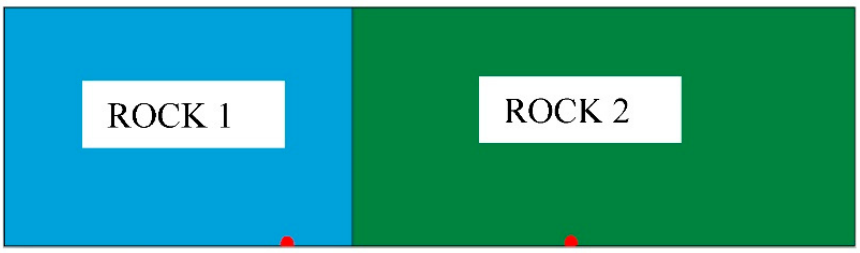


Figure 11. Rock contact model.

Several techniques are applied to analyze the influence of stress wave interaction on rock fracturing across the contact, such as varying the firing direction, varying the initiation delays, and varying the distance from the first blasthole to the contact. From the results in Figure 12, when the contact is at 1.5 m and monitoring points are set up at distances of 1 m and 2 m, after firing a single blasthole, it is observed that the stress wave is enhanced from soft rock to hard rock (compare b to d), and it attenuates in the opposite direction (compare a to c).

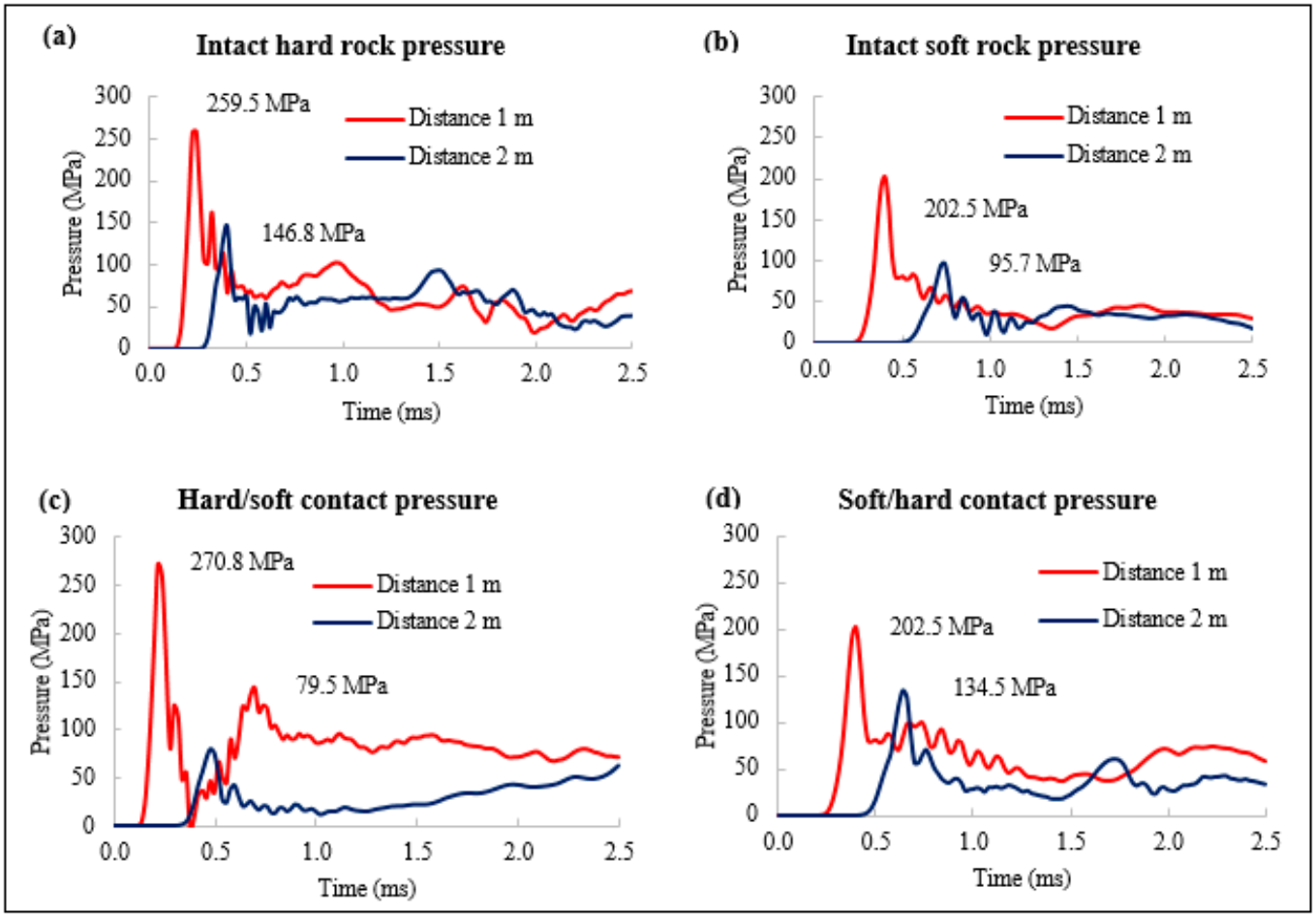


Figure 12. Stress wave across the contacts.

Firing two adjacent blastholes across a contact, Case A analyzes the firing sequence and found that it is from 'hard to soft' (H-S), and the interface is at 1.5 m; the second charge (on soft rock) is fired at variable delays. With increasing delays, the damage to the soft rock declines, as shown in Figure 13a,b. The stress wave from the first blasthole influences detonation on the second hole with shorter (near-instantaneous) initiation, as seen in 0.3 and 0.5 ms delays in Figure 13b.

Figure 13c shows the peak stress monitored from various distances. The first peak at a distance of 1 m is caused by the wave reflection at the contact followed by rapid attenuation across the contact, as observed at a distance of 2 m. The wave interaction occurs at various distances depending on the timing delay. The increased delay allows for more fractures to form across the joint from the first hole, while the development of fractures around the second hole is significantly halted by the increased confinement, as seen in Figure 13a.

In the second case (Case B), the firing sequence is from soft to hard; the interface is at 1.5 m, and the blasthole on a hard rock is fired at various delays. The damage contours in Figure 14a and the plot in Figure 14b show that damage is the highest at the 0.3 ms delay, with a 5% improvement in damage. The stress wave is enhanced through the contact, and as the delay increases, the confinement shifts towards the second hole, as observed in the damage contours in Figure 14a and peak stress curves for various distances in Figure 14c.

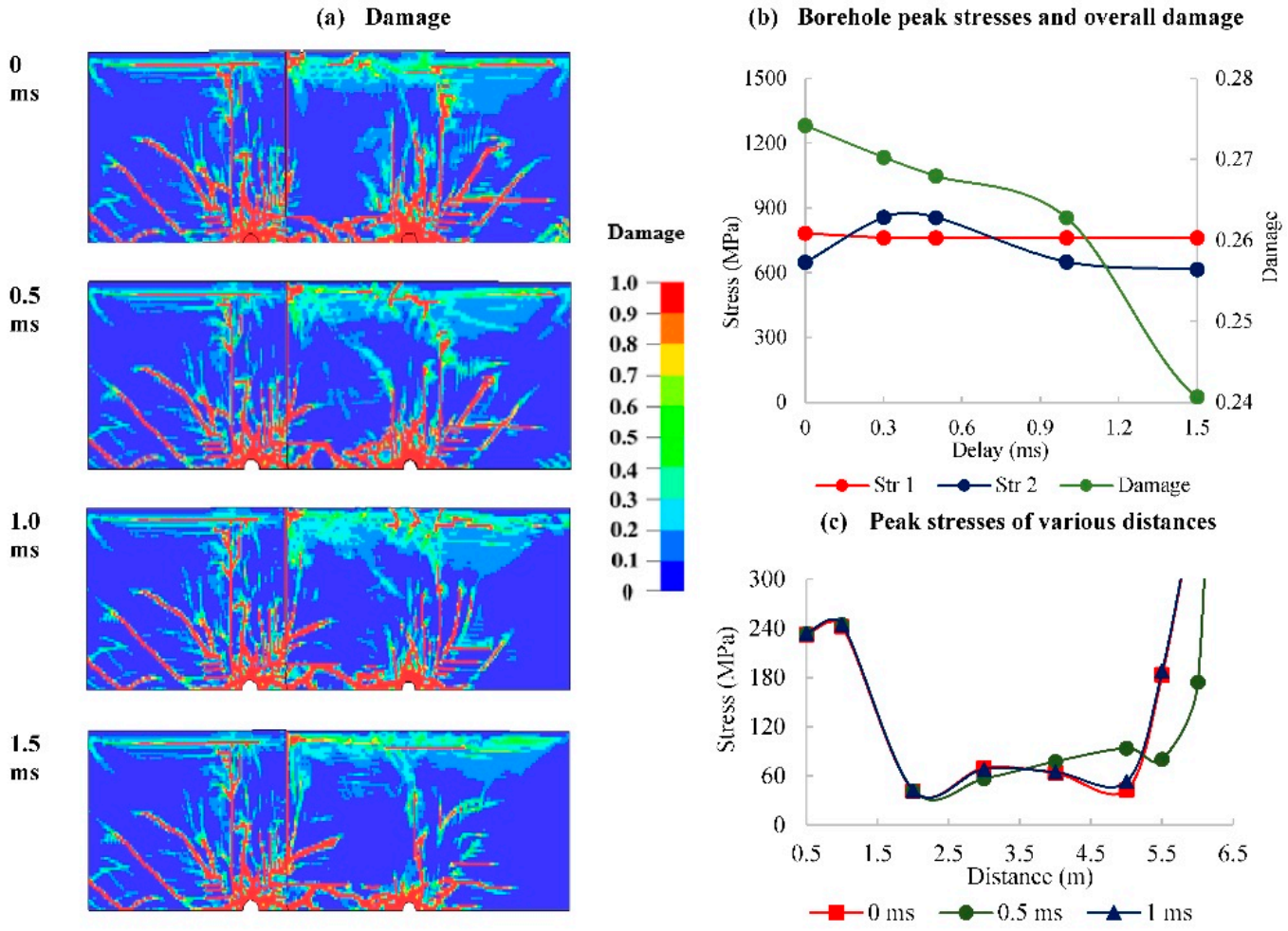


Figure 13. Case A—damage distribution after firing the hard rock first.

At the 0 ms delay, a larger area between blastholes is affected by the high confinement between blastholes. As the delay increases to 0.3 ms, most of the fractures around the first hole are formed before the second one detonates, and because the delay is shorter and the wave travels at a slower speed in the soft rock, the second hole is not affected. As the delay further increases, more fractures are formed around the first hole and across the joint before the second charge detonates. Considering that the stress wave is enhanced from soft to hard rock, the stress wave interaction shifts towards the second hole and reduces fracturing, as seen in the 1 ms delay in Figure 14a,c.

In the third case (Case C), the firing sequence is from soft to hard; the interface is at 5.0 m from the first charge and 1.5 m from the second; the second charge (on a hard rock) is fired at various delays. The results in Figure 15 suggest that the use of longer delays allows fractures to form around the first rock before the second hole detonates. Shorter delays permit fracture development beyond the contact from the second charge, but the higher confinement limits fracture development around the blasthole and the contact on the first charge side. The improvements in fracturing are achieved by longer delays. The optimum delay in this case is 1.2 ms, with a fracture improvement of 7%; beyond 1.2 ms, no further improvements occur, as seen in Figure 15b.

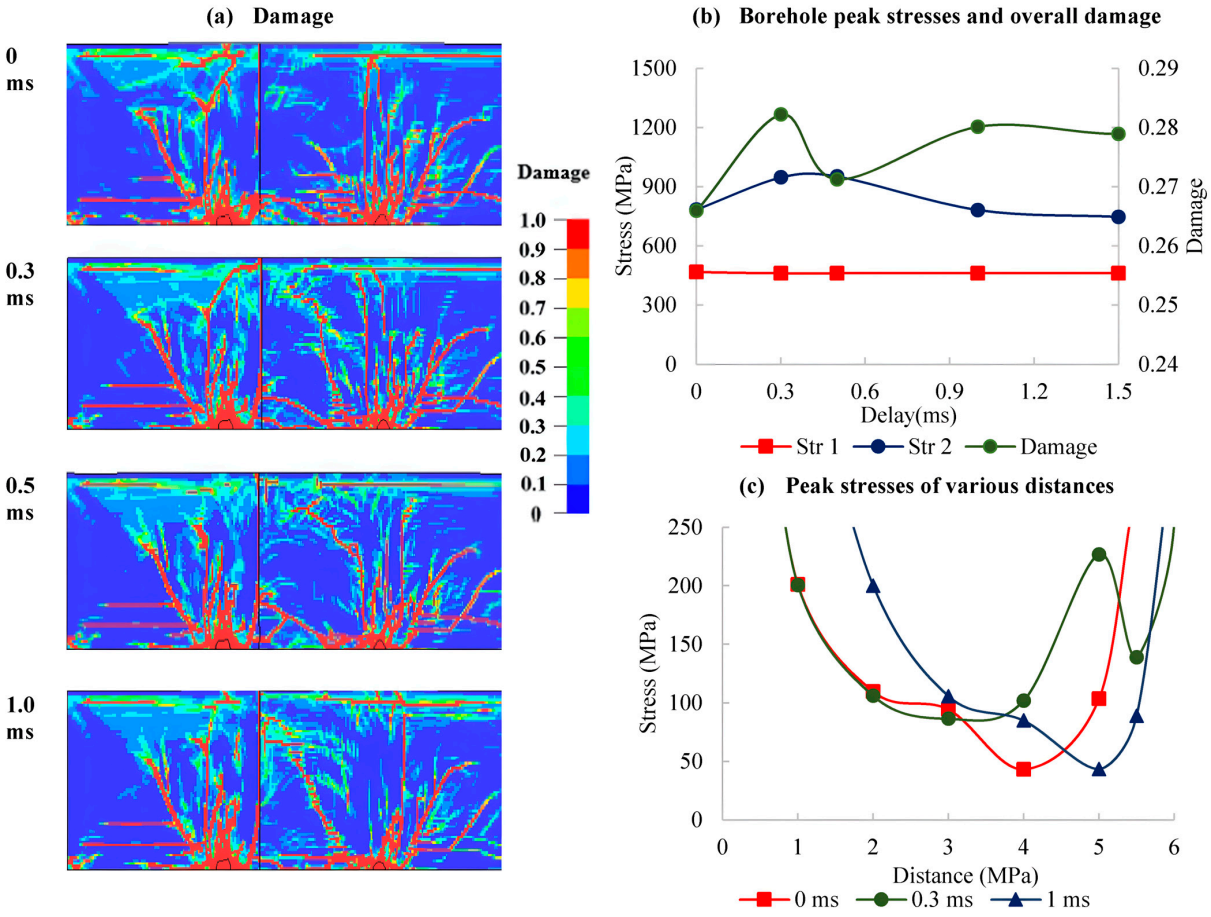


Figure 14. Case B—damage distribution when firing the soft rock first.

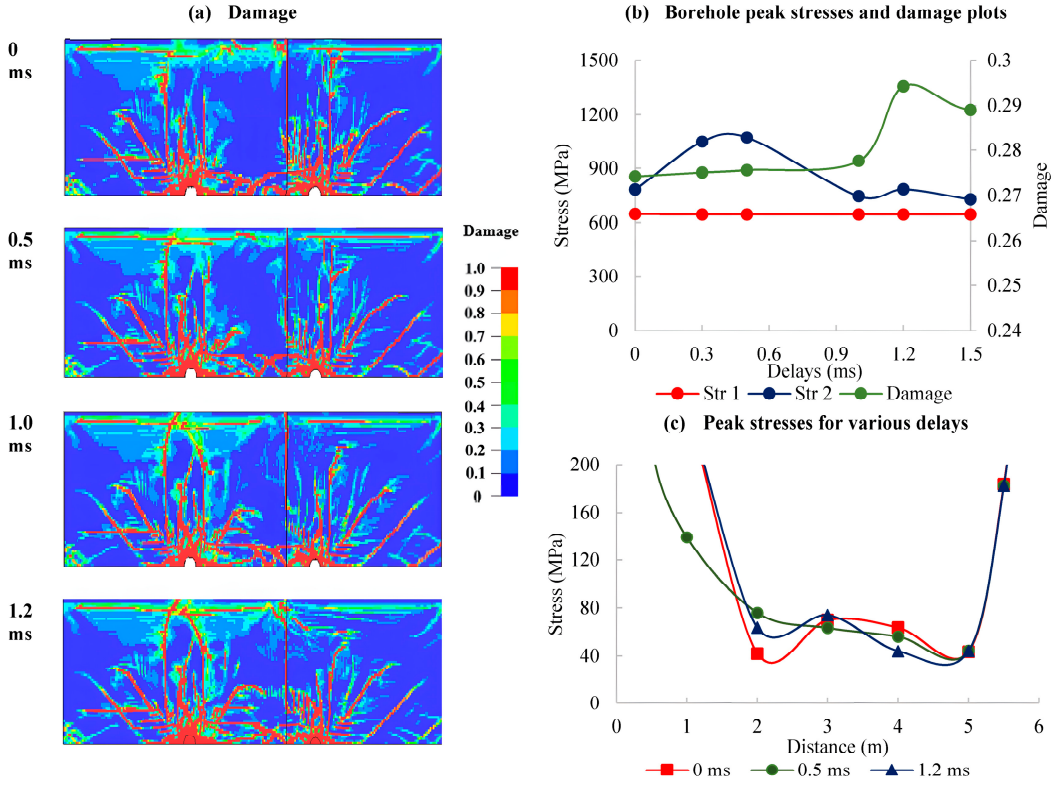


Figure 15. Case C—damage distribution when firing the soft rock first with a longer interface.

3.3. Stress Wave Interaction Across the Joint

Other common features in rock mass formation are the joints that can appear alone or in a family with the same properties and orientation, termed joint sets. Joints are formed from the brittle fracture of rock, usually through tensile stress. The joints can be empty or filled with various minerals or materials such as clay, sand, etc. The analysis covers joints filled with clay and empty joints.

3.3.1. Clay Infill

A single joint located 1.5 m from the first blasthole, 10 cm wide, filled with clay material with properties in Table 5, is studied to assess the influence of joints in stress wave interactions between blastholes. The main rock is BIF. The joint is modelled as the plastic kinematic material and a Lagrangian part.

Table 5. Clay infill properties.

Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio	Yield Stress, (MPa)	Tangent Modulus, (GPa)	Hardening Parameter	Failure Strain, FS
1160	5	0.35	0.4	4	0	0.5

Two cases are studied; in the first case, a closer charge to the joint is fired first, followed by the second charge at various delays. In the second case, the further hole is fired first, followed by the close charge at various delays. The results indicate that when the closer charge is fired first, with appropriate delay to the detonation of the further charge, the fractures develop across the joint with fewer interactions between the holes. A further increase in delay interferes with the formation of fractures around the second charge, as seen in the 1.2 ms delay in Figure 16.

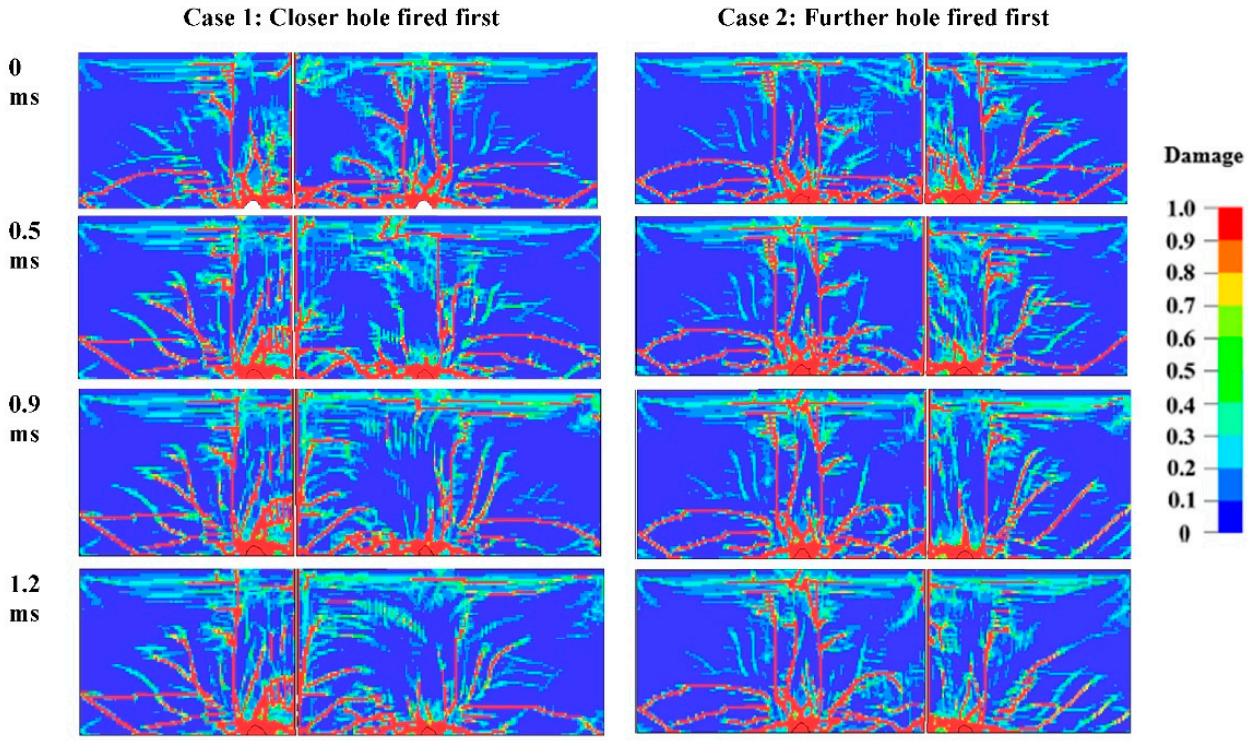


Figure 16. Damage across the joint for various delays.

In Case 2, when the further charge is fired first, the stress wave attenuates upon reaching the joint. With shorter delays, the interaction between stress waves from both

holes hinders fracturing around the joint on the first charge side. For further delays, for example, between 0.9 and 1.2 ms, fractures develop with minimal interference from the second hole, improving fracturing. Beyond the 1.2 ms delay, fracturing around the second hole is repressed.

The optimum delay is suggested to be 0.9 ms regardless of the firing direction, with better results obtained when the charge closer to the joint is fired first, as illustrated in Figure 17a. The fracturing improvement for Case 1 and Case 2 is 14% and 5%, respectively. The stress plot in Figure 17b indicates a smooth transition of the peak stress along the bench when the delay is 0.9 ms, which, as seen for the intact rock in Section 3.1, results in better fracturing. Fracturing a jointed rock mass requires a slightly shorter delay (0.9 ms) than the intact rock (1 ms) since the stress waves attenuate at the joint and weaken the interference when they converge.

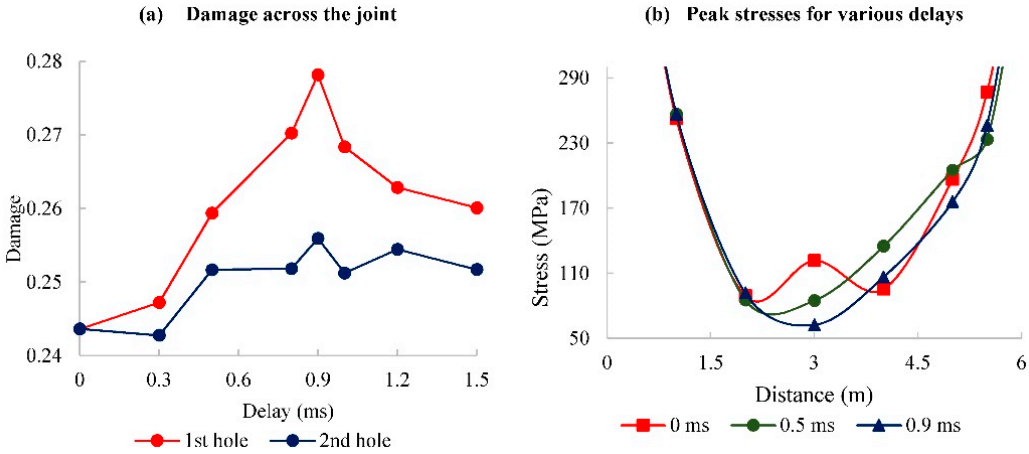


Figure 17. Damage and stress plots for the stress interaction across the joint.

3.3.2. Empty Joints

Similar to the clay-filled joint, an empty 10 cm wide joint is introduced through a BIF rock 1.5 m from the first blasthole. A NULL material model and a polynomial equation of state are used to model the joint. Air is modelled as an Eulerial part. The material and equation of state properties are shown in Table 6. Similar cases to the clay-filled joint are analyzed.

Table 6. Air properties.

Density (kg/m^3)	C4	C5	C6	E_o (MPa)	V_o
1.29	0.4	0.4	0	0.5	1

The results in Figure 18 indicate that when there is a wider empty joint between the blastholes, regardless of the firing sequence, the two holes act as individual charges with the least to no interaction between them; that is, the joint acts as a free face from which most to all of the energy is reflected. The maximum fracturing is obtained when the holes are fired simultaneously; no improvement is seen when delays are introduced. For a narrower joint (3 mm), a slight improvement of 0.3% is observed when the further hole is detonated 0.25 ms ahead of the closer hole, which is insignificant.

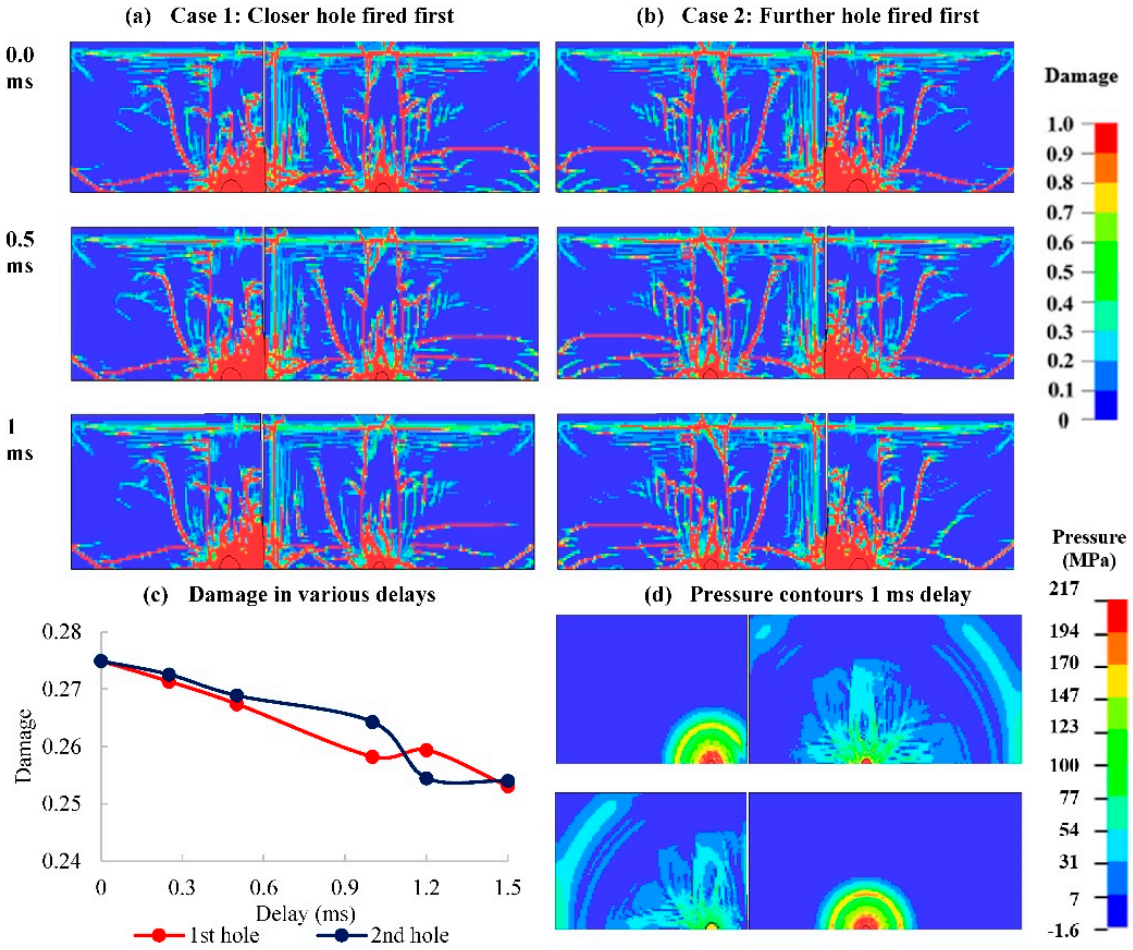


Figure 18. Damage distribution across an empty joint.

4. Discussion and Application in the Blasting

Section 3 covered the analysis of the stress wave interaction between blastholes on various rock masses. The analysis considered intact rock, the interface between soft and hard rocks, and hard rock with a joint between blastholes, with one scenario with a clay-filled joint and the other with an empty joint. It has been observed that the interaction between blastholes is a significant factor in the development and distribution of fractures from blasting. Various rock properties influence the interaction differently, so the decision on initiation sequence and delays are critical for achieving good fragmentation. Figure 19 summarizes the analysis.

Wave superimposition affects fracturing differently. What is observed is that at different delays and rock mass properties, stress wave superimposition causes various outcomes. Significant influence is observed in hard–soft rock contacts, where the compression wave from the hard rock impedes soft rock fracturing by increasing its confinement when the hard rock is initiated first. Dampening stress waves through joints reduces stress wave destructive superimposition and improves fracturing on the jointed rock mass at an optimum delay. From the conflicting literature discussed in Section 1, this study suggests that wave interactions can result in either constructive (phase enhancement) or destructive (attenuation) effects depending on the properties of the media, the sequence, and the delays that govern stress wave alignment.

Fracturing can be increased by 10% damage volume on the intact rock by using a delay between adjacent charge initiations; the firing direction does not have an influence. The delay should ensure that fractures around the first hole are formed with minimum

interference on the detonation and fracturing of the succeeding hole. Shorter delays increase destructive stress wave interference between the blastholes, causing less fracturing. Longer delays hinder fracture development around the succeeding hole. Similar findings from the numerical simulation and laboratory-scale tests were reported by Saadatmand Hashemi and Katsabanis [12] and Johansson and Ouchterlony [10].

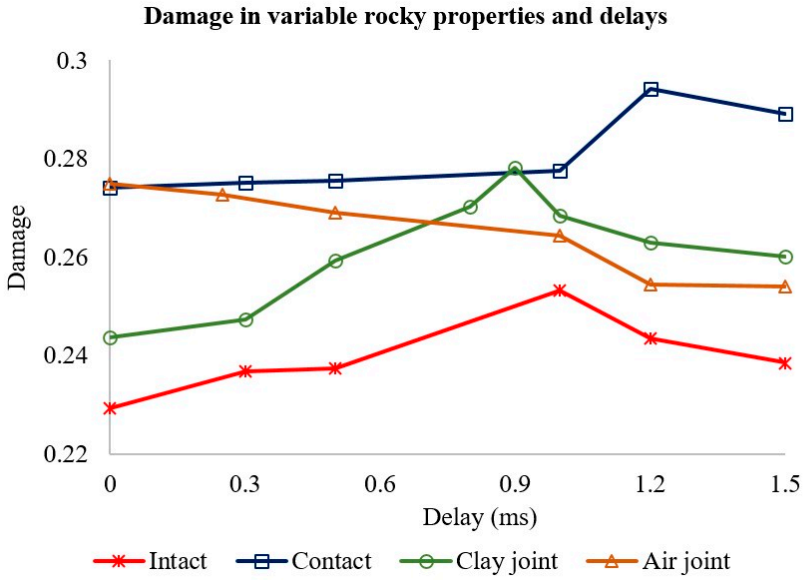


Figure 19. Analysis summary.

The same concept applies to the other rock mass properties. The firing direction from hard rock to soft rock increases confinement on the soft rock, resulting in less fracturing regardless of the delay. Firing soft rock first increases fracturing by 7% with the optimum delay, which in this case is 1.2 ms, slightly higher than 1 ms for the intact hard rock. Additional delays are explained by the fact that the wave travels slower in the soft rock than in hard rock, in addition to disruptions at the interface. Overall damage is higher than a hard rock due to the application of a higher-strength explosive on a softer rock.

When a clay-filled joint is cutting across two blastholes, a good fracturing is achieved by first firing the blasthole closer to the structure, allowing enough delay for the fractures to form around the blasthole and across the joint, and the attenuations from the interaction of stress waves with the joint lower the disruption of fracture formation around the succeeding blasthole. The optimum delay is slightly less than the intact rock (0.9 ms) since some energy is reflected at the joint, minimizing destructive interactions with the succeeding blasthole. Overall damage increases compared to intact rock from the interaction of the stress wave with the joint's interface, similar to the observations made by Dotto and Pourrahimian [18].

When the joint is empty, the blastholes act as independent charges with fewer interactions. The joint acts as a free face from which most or all of the energy reflects. Sequential initiation does not improve fracturing, making simultaneous initiation a favourable option. However, firing the further hole first at a near-instantaneous delay may slightly improve fracturing. Careful consideration is required as this approach may also increase ground vibrations.

5. Conclusions

This study investigated the effect of initiation sequences and delays on fracturing across different rock mass properties using numerical simulations. Both 3D and 2D models were used in the study. The 3D models provide a better understanding of the damage distribution in a three-dimensional set up such as a bench. A 2D model is a simplified

computation favourable for analyzing the damage distribution in a plane of choice. Comparisons between the models indicate that while the overall extent and distribution of fractures are similar, the 2D model tends to overestimate fracture intensity.

The observed fracturing patterns for various rock masses suggest that appropriate initiation sequences and delays can enhance fragmentation between adjacent blastholes. An optimum delay allows enough time for fractures to form on the preceding blasthole before firing the succeeding and the stress wave to attenuate, resulting in less interference with the detonation and formation of fractures on the subsequent. With a suitable delay, the wave pulse can be enhanced through constructive interactions between stress waves from the adjacent holes, resulting in better fracturing.

While the initiation sequence may not be a significant factor when blasting the intact rock, it is vital when dealing with a varying rock mass. When blasting through the contact of soft and hard rocks, fracturing patterns suggest that fragmentation improves when firing from soft to hard rock. The opposite increases confinement on the soft rock in addition to destructive stress wave interactions, halting fracturing significantly. The delay through contacts can be slightly higher than in the intact hard rock blasting due to a lower stress wave speed on the soft rock.

Depending on the type and properties of the joints' infill material, fracturing may be improved by initiation delays and the firing direction. For clay-filled joints, fracturing may be improved by first detonating the charge closest to the joint. With an optimum delay, fractures initiate around the first charge and propagate across the joint before the next blasthole is fired, minimizing the interaction between successive detonations. The optimal timing is slightly shorter than in intact hard rock, as the stress wave attenuates through the joint, reducing interactions between adjacent blastholes.

Initiation delays do not improve fragmentation when blasting adjacent blastholes separated by an empty joint. The joint acts as a free face from which most or all energy from the stress wave is reflected. In this study, an insignificant improvement was observed on a narrower joint when firing the further blasthole from the joint first at near-instantaneous delays.

Overall, no general sequencing or delay selection is suitable for all blasting environments. The study suggests that the wave propagation properties on the encountered intact rock can determine the base delay. Geological structures influence propagation mechanisms and may require adjustments to firing sequences and delays to improve fracturing. An exception is observed when encountering empty joints.

The conclusions in this study are based on numerical simulations where improved fragmentation is inferred from increased fracturing. Further validation using real case fragmentation analysis is necessary to substantiate these findings. Several factors can in-fluence multi-hole blast-induced fracturing in non-uniform rock masses. This study focused only on the initiation sequence and delays. Future research could explore variations in blast hole spacing and explosive properties to assess their impact. Additionally, studies could investigate longer delay times, including the 8 ms rule, to evaluate shock wave superimposition and develop a delay time model for discontinuous rock mass.

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