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Full Paper

INFLUENCE OF JOINT ORIENTATION ON BLAST-INDUCED FRACTURE PATTERNS IN GRANITE ROCK USING DISCRETE ELEMENT METHOD

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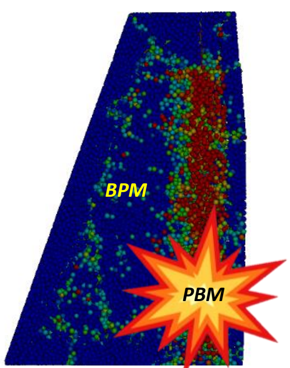
Graphical abstract



Abstract

Blasting is widely used for rock fragmentation in quarries, but the presence of geological discontinuities (joints) disrupts the process, often resulting in uneconomic muck-piles and unstable post-blast surfaces. The primary objective of this study is to observe the effect of discontinuity orientation on development of fracture pattern in rock through numerical analysis. Discrete element method (DEM) was utilized to develop one solid and four discontinuous models of rock bench with variable joint orientations, using the Bonded Particle Model for rock material and Particle Blast Method for blast loading. The joint hinders fracture development, allowing the blast energy to dissipate through void. Dominant fractures develop within 20 ms in the solid model, whereas the discontinuous model with a larger dip and dip direction (70°, 174°) does not exhibit significant cracking within this timeframe. The angle between the dip direction and the normal axis of the free face influences fracture generation mostly; when these align, the risk of slab failure and the formation of large rock fragments intensifies. Overall, DEM can be utilized to simulate the blast operation, and the findings of this research can aid in deciding the right orientation and appropriate delay time for blast operation in rock quarries.

Keywords: Joint Orientation, Rock Fragmentation, Bonded Particle Model, Particle Blast Method, Discrete Element Method

1.0 INTRODUCTION

Blasting is a widely used technique in mining and civil engineering industries to fragment rock, especially in quarries, mines, and excavation sites for construction (Xu et al., 2022). The economic viability of this technique has amplified its role in these industries, leading to significant advancements in numerical modeling frameworks aimed at improving the prediction and control of blast-induced fragmentation (Mitchell et al., 2023). Optimal fragmentation is critical in the mining production value chain as it increases machinery efficiency, reduces maintenance costs, and maximizes crusher output, ultimately lowering operational expenses (Abbaspour et al., 2018, Bilim et al., 2017). However, achieving the desired size distribution of rock fragments is challenging due to the inherent nonhomogeneous properties of the rock mass and the presence of natural discontinuities, such as joints, faults, and bedding planes, etc. These discontinuities, which arise from geological processes like tectonic movements and diastrophism, create zones of weakness in rock masses, impacting fragmentation behavior and making outcomes unpredictable (Bakar, 2013). Blasting granite presents several challenges due to its physical and structural characteristics. Its high compressive strength (typically 100–250 MPa) and toughness demand greater explosive energy and precise blast design to ensure effective fragmentation (Bell, 2007). The rock's low porosity (<1%) restricts gas penetration, which limits energy transfer during detonation and reduces blasting efficiency (Selby, 1993). Additionally, granite commonly features orthogonal joint systems, which can either facilitate breakage or cause uneven fragmentation and flyrock if joints are widely spaced or unfavorably oriented (Twidale & Vidal Romaní, 2005). Poor jointing may also lead to overbreak and excessive vibration, particularly in controlled blasting environments. Achieving uniform fragmentation in granite is difficult, often resulting in oversized boulders that hinder loading and crushing operations (Singh & Roy, 2005). This unpredictability can compromise the economic value of fragmented rock piles and increase the risk of instability in post-blast surfaces. The impact of existing discontinuities on rock mass fragmentation from blasting has been extensively researched in recent years. Studies have utilized both numerical models and laboratory tests to examine how joints affect fragmentation behavior. Wang et al. (2018) incorporated joints in a DEM model and found that crack intensity was highest in the zone between the joint contact surface and the blasthole. Singh and Narendrula (2007) conducted experimental investigations into joint orientation, finding that the most significant overbreak occurred with joints at a 45^{o} angle, while minimal damage was observed for samples with vertically aligned joints. Himanshu et al. (2023) examined joints with bonded and frictional properties in their study which revealed that closely spaced joints produced the highest volume of fragmented rock. Xue et al. (2022) applied the Bonded Particle Model (BPM) to explore various joint orientations, showing that models with horizontal and vertical discontinuities developed cracks from the blasthole, while inclined discontinuities generated cracks from the joint surface. A deep understanding of the fragmentation process is essential for ensuring economic, safety, and environmental sustainability. Properly managed blast designs optimize rock fragmentation, which otherwise may lead to adverse effects like ground vibration, fly rock, air blasts, and back break (Shahrin et al., 2019). Since it is impractical to conduct field experiments to evaluate the influence of discontinuity on blast fragmentation, numerical analysis serves as an effective alternative. This study employs the DEM to simulate post-blast conditions in granite rock containing discontinuities, specifically examining how joint orientation affects the propagation of the blast-induced fractures. Through this exploration, this research aims to advance the understanding of blast fragmentation in discontinuous rock mass to optimize the blast designs for enhancing both safety and cost-efficiency in rock fragmentation operations.

2.0 METHODOLOGY

2.1 Research Method

Numerical simulation of rock bench models was conducted in this study using commercial software, LS-DYNA, where the DEM was employed to simulate the blasting process. From post-blast analysis, the blast-induced fragmentation pattern was observed. Figure 1 represents the flowchart of work carried out in this research.

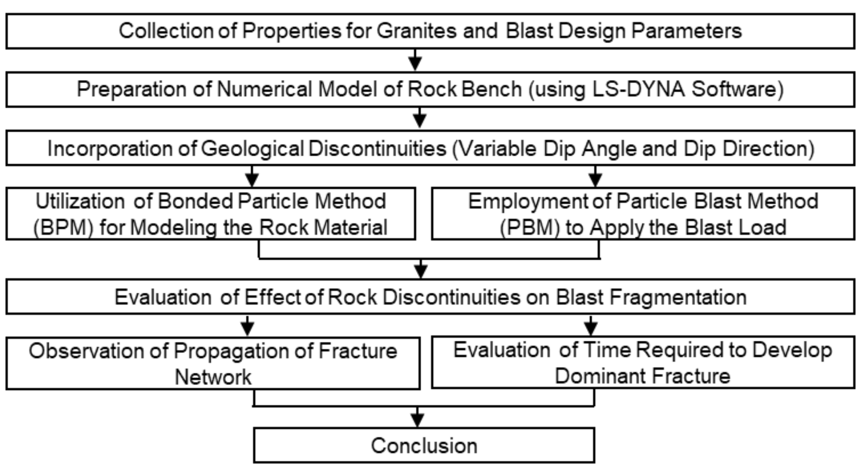


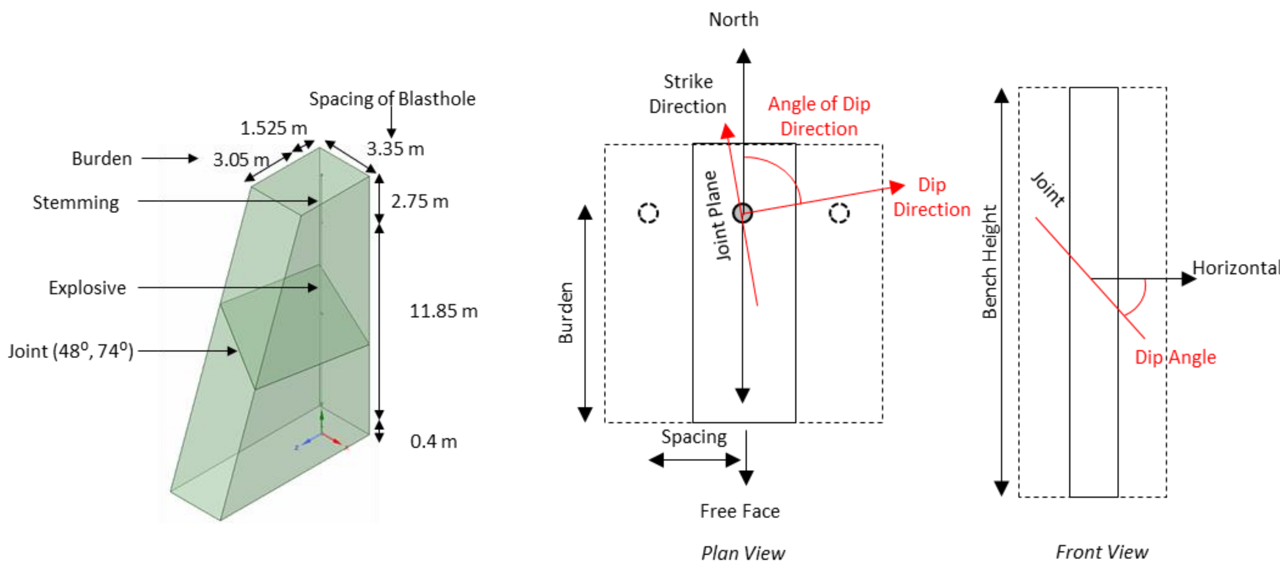
Figure 1 Flow chart of this research

2.2 Description of Numerical Model

To examine the impact of joints and their orientation on rock blast fragmentation, five rock bench models were created. To represent a uniform rock body, one model (Model 1) was made as a solid with no joints. Each of the four remaining models, Model 2 through Model 5, has a single joint with a variable dip angle and orientation. The joint was manually created and left void to represent the real field scenario. The specific blast design parameters are listed in Table 1 and the geometry of the rock bench model is illustrated in Figure 2 (a). The creation of joint plane and assigning dip angle and dip direction is shown in Figure 2 (b). A tabulated summary of the orientation of the joint (dip angle and dip direction) incorporated in the model is shown in Table 2. Identity of these models are denoted as Model ID (Dip Angle, Dip Direction) in this study.

Table 1 Parameters adopted for blast design of the rock bench

Parameter	Value	Parameter	Value
Hole Diameter (mm)	89	Stemming Material	Chipping Stone
Average hole Depth (m)	14.6	Dip of Borehole (°)	90
Bench Height (m)	15.0	Blast Pattern	Staggered
Sub-drill (m)	0.5		
Burden (m)	3.05	Explosive	Bulk Emulsion
Spacing (m)	3.35	Powder Factor	0.38
Stemming Length(m)	2.75	Charge per Delay (kg)	7000



(a) (b)

Figure 2 (a) Geometry of the rock bench model and (b) Creation of joint on the rock bench model

Table 2 Description of discontinuity orientation incorporated into the numerical models

Model Identity	Dip Angle	Dip Direction
Model 1	Solid (No Joint)	
Model 2	48°	74°
Model 3	70°	74°
Model 4	48°	164°
Model 5	70°	164°

2.3 Bonded Particle Model

The geomechanical characteristics of rock masses are represented by a wide range of material models, some of which are specially designed to simulate the impact of blast loading. Potyondy and Cundall (2004) stated that a cement-based granular mortar of complex-shaped granular particles can represent the mechanical behavior of rock where deformation and rupture of the grains and the cement may occur. The geomechanical characteristics of rock are mostly determined by its contents and particle structure, but they are also greatly influenced by the geological processes of rock formation, growth, and existing geological discontinuities in the rock mass. In this study, the linear elastic material model was employed to incorporate the geomechanical properties of the rock by the MAT_ELASTIC keyword with the following parameters (see Table 3).

Table 3 Geomechanical Properties of Rock

Parameters	Value	Parameters	Value
Density (kg/m³)	2600	Young's modulus of elasticity (MPa)	3370
Poisson's ratio	0.2	Uniaxial compression strength (MPa)	71
Shear strength (MPa)	2.4	Uniaxial tensile strength (MPa)	12.6

To model the behavior of rock mass as an aggregation of particles to simulate the fracture, the Bonded Particle Model (BPM) was utilized which was introduced by Potyondy and Cundall (2004). This approach models rock as a densely packed assembly of particles of varying sizes, which are circular in two dimensions or spheroidal in three dimensions. These particles are connected by parallel bonds at their contact points. While these bonds operate independently of the DEM, each bond can account for tensile, bending, shear, and torsional forces, effectively capturing the full range of mechanical behavior seen in solid mechanics (Karajan et al., 2013). Commercial software like PFC and LS-DYNA can simulate mechanical behavior using DEM (Potyondy, 2015).

The rock bench model was discretized into DEM particles to investigate the blast-induce fragmentation. To ensure that the total mass of the simulated assembly of DEM particles matched the real rock mass, the density of DEM particle was calibrated. The previously calibrated micro-properties of BPM used by Shahrin et al. (2022) which demonstrated similar behavior to actual rock have been assigned for numerical model and shown in Table 4. Figure 3 displays visual representations of these DEM models.

Table 4 Input parameters for BPM from the calibrated model

Properties	Value	Properties	Value
Particle radius/mm	100-125	MAXGAP	-1.31
PBN (GPa)	20.76	NDAMP	0.7
PBS	0.25	TDAMP	0.01
PBN_S	0.03	Fric	0.99
PBS_S	0.02	FricR	0.98
SFA	1.31	NormK	0.1
ALPHA	0.5	ShearK	0.4

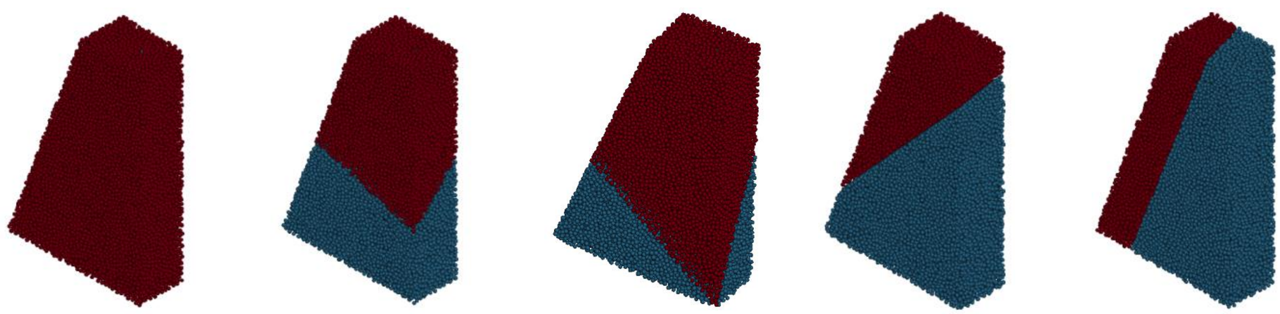


Figure 3 DEM model of the rock bench

2.4 Particle Blast Method

While the continuum-based Eulerian approach is among the most accurate methods for simulating blast load pattern, it has certain limitations, such as advection errors. Additionally, handling advection effects and complex geometries in this model demands substantial computational resources. To address these challenges, the Corpuscular Particle Method (CPM) was introduced, particularly for airbag deployment simulations. CPM can consider transient gas dynamics and thermodynamics by representing a group of gas molecules as particles with both translational and rotational energy (Teng, 2016). However, CPM assumes a thermally equilibrium state, which is suitable for moderate temperatures and lower pressures, as in airbag simulations, but is not appropriate for blast load simulations, where high gas flow invalidates this assumption of thermal equilibrium. To enhance the capability of CPM, the Particle Blast Model (PBM) was developed. PBM can simulate the thermally non-equilibrium conditions created by blast loads by modeling complex interactions between explosives, air, and structures. In PBM, particle-structure interactions are purely elastic, with each particle containing both translational and rotational energy. The dynamic behavior of gas is realistically represented by particle collisions, and temperature controls the balance between translational and rotational energy. Additionally, co-volume effects are considered to better capture gas behavior at elevated temperatures (Teng and Wang, 2014).

Particle-based blast loading was employed in this study using the PARTICLE_BLAST keyword to simulate the blast load. The particle blast model represented the explosive material, consisting of 50,000 high-explosive (HE) particles, with the following input parameters for explosive properties tabulated in Table 5. The geometry of a high explosive was defined as the same as the explosive column in the blast design and the domain was defined using the DEFINE_PBLAST_GEOMETRY keyword.

Table 5 Characteristics of explosive

Parameters	Value
Density, ρ (kg/m)	1200
Energy, E (GJ/m)	3.2
Detonation velocity, D (m/s)	4500
High Explosive fraction, γ	1.4
Co-volume, b	0.3

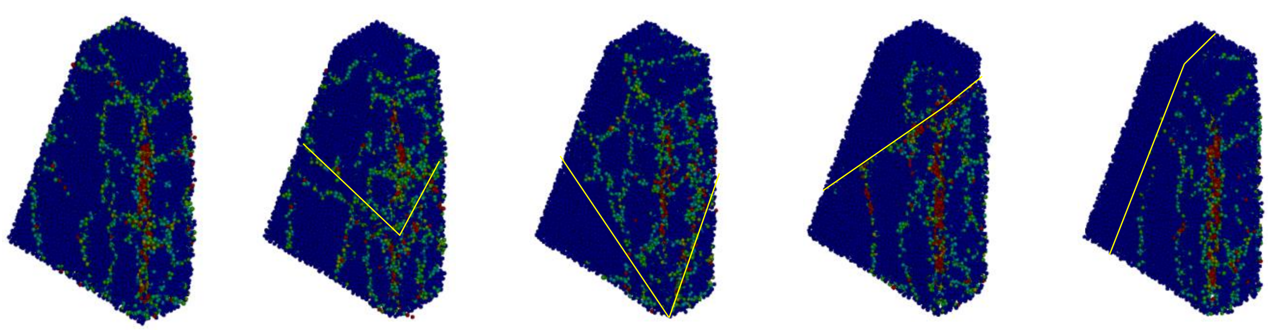
3.0 RESULTS AND DISCUSSION

After analyzing the explosion in rock mass numerically, the fracture pattern was observed in the DEM models of the rock bench. The numerically simulated damage percentage was studied where the degree of damage is shown by the color intensity. The green particles indicate the initiation of a fracture, while the red particles represent damaged particles (completely failed). By linking green particles that experienced overstress and surpassed bond strength, ultimately resulting in bond failure, the fracture pattern can be predicted. From the section view of the rock bench at various times, the amount of time required to create the dominant fracture was also assessed.

3.1 Propagation of Fracture

From the post-blast analysis of the rock bench models, the fragmentation pattern was obtained for 30th milliseconds. In the solid rock model (Model-1), a higher fracture density was observed, indicating that the blast energy could propagate efficiently through the rock mass (see Figure 4(a)). In contrast, when joints were introduced, the fracture density decreased. For instance, in Model-2 (48^o,74^o), fewer fractures appeared in the upper section of the bench, above the joint, as the joint facilitate to dissipate the blast energy through the voids, shown in Figure 4(b). As the joint steepened in Model-3 (70^o,74^o), the fracture density further decreased. Figure 4(c) illustrates the fracture pattern for Model-3. The steeper joint angles (greater dip angle) increased the projected area at the rock bench which is functioning as a damper and allowed more energy to dissipate along the joint. Consequently, this greater dissipation of energy led to the formation of larger rock fragments.

A change in dip direction brings a substantial change in the blast-induced fracture pattern. In Model-4 (48^o,164^o) and Model-5 (70^o,164^o), fracture density was significantly reduced. This decrease can be attributed to the dip direction becoming nearly perpendicular to the free face, which most effectively obstructs the transmission of blast energy. In these configurations, the joint acts as a direct barrier between the blast initiation source and the burden, impeding energy propagation. In the case of Model-5 (70^o,164^o), with a steeper dip angle of 70^o, the front section of the rock bench remained largely unfragmented even at 30 milliseconds post-blast. Figure 4(d) and Figure 4(e) illustrate these models, respectively. This combination of dip angle and dip direction for joint orientation amplifies the potency of slab or toppling failure following blasting activities, as the energy distribution is less uniform and results in greater instability in the rock mass. Therefore, these specific orientations intensify the risks for structural stability during blasting and may cause slab failure or toppling failure.



(a) Model 1(Solid) (b) Model 2 (48^o,74^o) (c) Model 3 (70^o,74^o) (d) Model 4 (48^o,164^o) (e) Model 5 (70^o,164^o)

Figure 4 Numerically simulated blast-induced fragmentation of the rock bench observed at 30th ms

3.2 Time Required to Develop Fracture

The gradual development of dominant fracture lines was monitored to determine the time required for the model to generate major cracks. This time is crucial for selecting an appropriate delay time, as excessive delay can hinder fragmentation by allowing energy to dissipate through the cracks generated from the initial blast. To examine the effect of joint orientation on fracture pattern formation, the fracture pattern in these DEM models were observed at the mid-section along the blasthole at specific intervals (15 ms, 20 ms, and 25 ms) which are shown in Figure 5.

From this study, it was observed that Model-1 (solid rock) developed dominant fracture lines within 20 ms, which became more pronounced over time. In contrast, Model 2 (48^o, 74^o) and Model 3 (70^o, 74^o) showed significant crack formation only at 20–25 ms as shown in in Figure 5(b) and Figure 5(c). No major cracking was detected in Models 4 (48°, 164°) and 5 (70°, 164°), especially on the upper block (left side of the joint) which is evident in Figure 5(d) and Figure 5(e). In the first set of models, where the angle between the dip direction and the normal axis of the free surface is smaller, blast energy effectively impacted the rock. However, in the latter set, with the dip direction nearly aligned with the normal axis of the free surface, energy transfer to the upper block was obstructed. The dip angle, however, did not significantly influence the development of the fracture pattern.

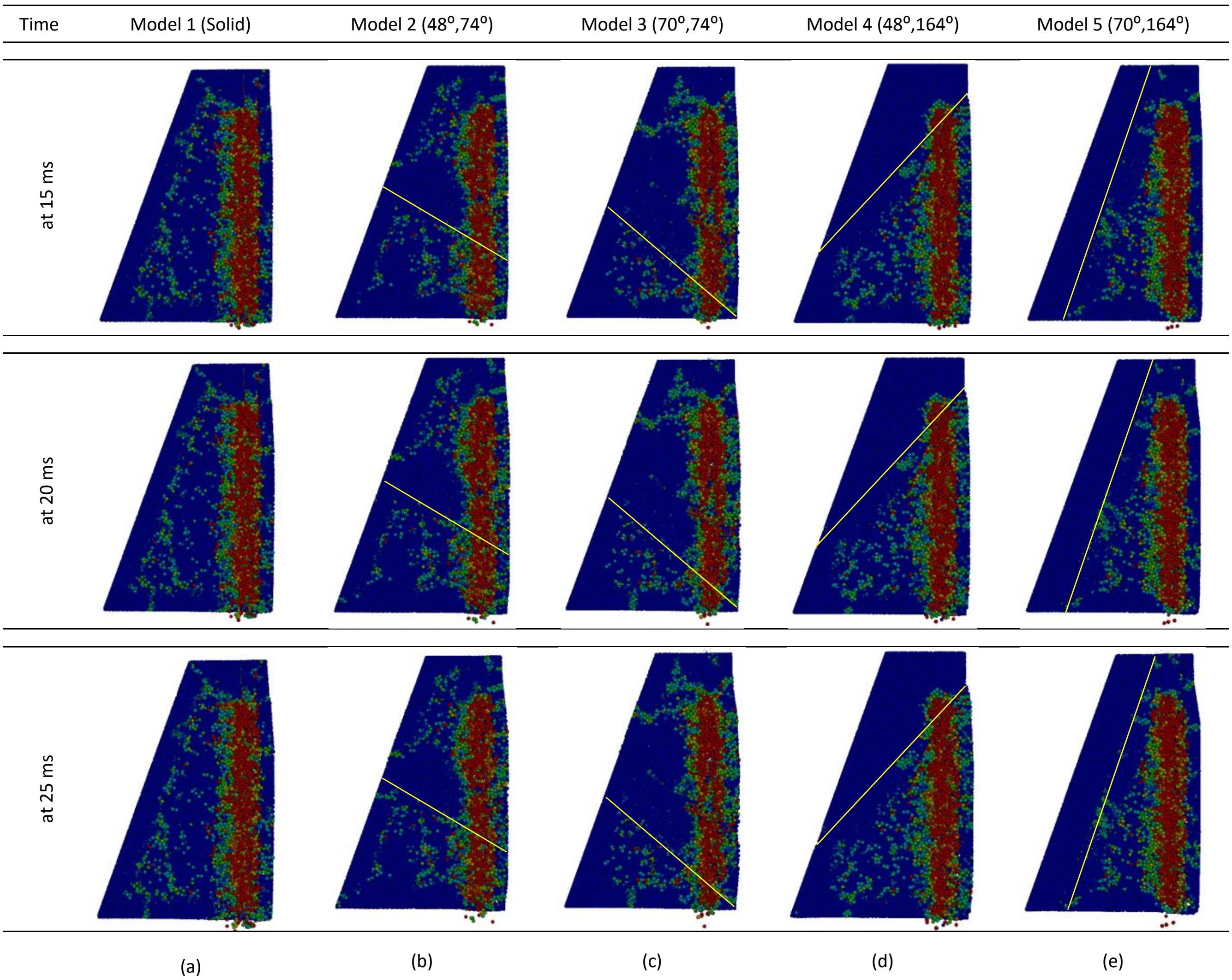


Figure 5 Observation of blast-induced crack propagation in the rock bench model at different time intervals

4.0 CONCLUSIONS

This study was conducted to assess the effect of joint orientation on blast-induced fracture pattern in rock mass using a discrete element model (DEM) with the Bonded Particle Model (BPM) for material representation and the Particle Blast Method (PBM) for blast loading. The analysis showed that joint orientation, particularly the dip direction, plays a vital role in determining fracture development, fragmentation density, and stability of the post-blast surface of rock mass. While the solid rock model quickly formed dominant fractures within 20 ms, models with varying joint orientations displayed delayed and less extensive fracture patterns. In particular, joints with larger dip and dip-direction angles (e.g. 70°, 164°) acted as barriers, obstructing blast energy transmission and resulting in fewer fractures and larger rock fragments. The dip direction being perpendicular to the free face increased the risk of structural instability by causing slab or toppling failure. Therefore, it necessitates careful consideration in blast design to mitigate potential failure mechanisms and optimize the fragmentation output. The blast operation should be oriented to maintain an angle close to 90° between the dip direction and the normal axis of the free surface. Additionally, for rock masses with lower joint density, the shortest delay time should be selected to maximize fragmentation. These findings indicate that the appropriate selection of delay time and joint orientation is essential for optimizing fragmentation and minimizing instability risks. DEM simulations effectively capture complex interactions in blast operations and provide valuable insights for improving rock blasting strategies, helping to achieve safer and more efficient quarry operations.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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